THE RELATION OF THE STRENGTH PROPERTIES OF MULTI-PLY PAPERBOARD TO THE BONDING BETWEEN PLIES

A thesis submitted by

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INTRODUCTION

In spite of the fact that about half of the paper products manufactured today are made from paperboard, the technical side of the production and properties of this important material have not received much attention. In recent years, the board industry has increased rapidly, but technical development has lagged behind. Furthermore, the results of most developments have been confined to the individual organization doing the work. Owing to these conditions, there is very little literature of a technical nature available to the board industry.

The manufacturer of paperboard is faced with a complexity of problems. Whereas the producer of fine paper is concerned with only one stock at a time, the manufacturer of multi-ply board must prepare and handle as many as four kinds of stock at the same time. The requirements that boxboard has to meet are no less demanding than those of many grades of paper; the board must have sufficient strength to fulfill use requirements, and in many cases it must have a good printing surface.

In paper made of a single ply, there are two primary strengths which affect the over-all strength of the sheet. These are the strength of the individual fibers and the strength of the bond between fibers. In multi-ply board, an additional primary strength exists--the force with which the plies are bonded together. The present investigation has been undertaken to determine some of the factors affecting this bonding between plies. The bonding will be related to the over-all strength of the sheet. From the effect of the different variables on the bonding force, an attempt has been made to ascertain the causes of this bonding. At the same time the results have direct practical applications.

The experimental work was carried out on sheets composed of different numbers of plies, made in a manner that approximated machine conditions as nearly as possible. The Noble and Wood sheetmaking apparatus was used for most of the work. Single sheets were couched one upon the other and then pressed and dried to give the final multi-ply sheet. Most of the work was carried out on two-ply sheets for preparation and testing simplicity, yet the results are applicable to sheets with a larger number of plies.

Although some of the properties of machine-made board, such as grain, must be sacrificed when handsheets are used in an investigation, it is believed that these are more than balanced by the additional control that is possible in the laboratory. A comparison between machine-made and handmade boards, prepared from identical stocks, showed that the strength properties of the two kinds of sheets were quite similar.

HISTORICAL REVIEW

The three primary strengths which are the components of the over-all strength of a multi-ply board are: (a) the strength of the individual fibers, (b) the strength of the bond between fibers, and (c) the strength of the bond between plies. Of these three factors, the first two have received a large amount of study, whereas the last has received almost none at all.

Many investigations, on bleaching for instance, have dealt with the effect of various factors on the fiber strength. Every day experimental beater runs are made to evaluate the Mullen and tear strength of pulps. These tests are related directly to the strength of the bond between fibers and the strength of the fibers. Doughty(1,2) has studied the effect of wet-pressing, which increases the fiber-to-fiber bonding force, on the tensile and other strength tests. He found that increased pressure caused an increase tensile strength. Therefore, an increased Mullen strength must also result, since Carson and Worthington(3), as well as Van den Akker(4), have shown the Mullen strength to be directly proportional to the tensile strength of the sheet.

Doughty was able to produce the same effect as beating by the use of increasing pressures for wet-pressing. In doing this, he increased the "solid fraction" of the sheet in much the same way that it is increased by beating. "The beating process may be divided into two parts, one in which strength increases are due to an actual change in the surface condition of the fiter, and the other in which such increases are due purely to solid fraction increase, dependent on increased shrinkage and therefore upon decreasing fiber particle size. The second of these effects can be duplicated by wet-pressing, the first cannot."

Some work has been done on the bonding between two sheets of paper or the bonding between two plies in a multiply board, but no one has seemed to recognize this bonding force as a primary force in the strength of the sheet. No attempt has been made to correlate it to the strength tests by which a sheet is usually characterized. However, very recently, Campbell(5) has shown that, in order to secure the best fold or bend in the manufacture of paperboard, it is necessary that the plies of the board split, one from the other, at the line of bonding when the bend is made. Contrary to the general belief, he pointed out that the top liner quality has little effect on the "bender" of the board, provided the board is scored and bent properly. Halladay and Ulm(6) have presented pictures of a good bend, showing how the plies of the board separate. In practical work it is necessary, therefore, that the bonding force be an optimum. Too high a force will result in too tight a sheet and give poor bending, but too low a bonding force will cause blows on the paper machine and picking on the printing presses.

When two or more sheets of wet paper, or mats of wet fibers, are couched together with the aid of a relatively low pressure, subsequently pressed at a relatively high pressure, and then dried, what causes these sheets to stick together? The answer to this specific question has not been reported in the literature. However, the closely related question of what causes bonding between fibers in a single sheet has been studied by several investigators.

Campbell has given the best explanation available at the present time(7,8). He postulated that fibers bond together on drying in the same way that two crystals bond together when they are partially dissolved by a trace of water and then dried in contact with each other. The cellulose crystals, or micelles, on the surface of the fiber are wet and hydrated. They may be said to be partially in solution. They are brought into contact with each other in the forming and pressing of the sheet on the paper machine. As the water is removed during the drying of the sheet, the crystals rearrange and, when two are in contact, their structures join to form a continuous structure. The process of beating merely increases the surface area of the fiber and allows a greater area of contact. The more the fibers are beaten, the greater the area of contact and the greater the extent of the bonding between fibers.

Sutermeister and Porter(9) have reported the use of a test to measure the bonding inside a single ply or sheet. They employed two brass plates, each exactly one inch square, and cemented sheets of paper between them by means of sodium silicate. The plates were equipped with hooks so that they could be pulled apart on the Schopper tensile tester. Typical values are given for the force required to split sheets of book papers. These forces varied between 26.4 pounds per square inch for a supercalendered sheet and 38.9 pounds per square inch for English finish book paper. The variations in a series of eight tests amounted to about plus or minus four pounds. Silicate was used, because it was found that, if properly applied, it did not penetrate even the most porous sheets.

Schupp and Boller(10), from their x-ray photographs of the silicate bonds in corrugated board, found that the silicate did not penetrate the sheet beyond a very thin surface layer. They concluded that, in this case, penetration is not necessary for good bonding.

Abrams(11) introduced a test very similar to that used by Sutermeister and Porter and used it to measure the bonding between plies in commercial boards. He employed wooden blocks, two inches square, and cemented the sheet between them with silicate. After the sheets had been seasoned for two hours, the force required to pull them apart was measured. Sutermeister pointed out that the time of seasoning the sheet after cementing it between the blocks had an effect on the values obtained. Care should be taken to carry out the tests under the same conditions each time. Abrams also compared the effect of the adhesives on the test, using a casein glue, a silicate, and a cellulose cement. He found that the adhesive had an effect, silicate giving the highest values. He gave the following as typical bonding forces:

16-point test liner.........	19.4 pounds per square inch
16-point test liner.........	11.3 pounds per square inch
27-point kraft board........	18.2 pounds per square inch
Machine-dried kraft pulp....	4.7 pounds per square inch

In comparing these tests with Sutermeister's values, he pointed out that the difference was probably due to the kind of stock used in making the sheets and the differences in the methods of conducting the tests. The amount of beating, rather than the differences in the test methods, plays the major role in determining the bonding force.

Bekk(12,13) has reported a commercial testing instrument which measures the force required to pick a sheet when shellac is used as the picking medium. He pointed out that supercalendered sheets have a surprisingly low pick value. This he attributed to "The grinding action of the calender rolls." He also pointed out that the sheets were two-sided with respect to picking.

The first and probably most widely used test to measure the bonding in printing papers or boards is the crude test of moistening the thumb, holding it firmly on the sheet for a few seconds, and then quickly pulling it away. The quality of the bond is determined by the amount of fiber removed. Griffin(14) recommended this test; Kirkpatrick(15) has also mentioned it. As a qualitative measure, it is fairly satisfactory.

Another method of measuring the resistance of sheets to picking is the use of standard waxes. These are usually made by compounding various percentages of a hard and soft wax. The K and N waxes are composed of different percentages of bayberry and carnauba waxes. At present, the standard waxes are used mostly for coated sheets, but their use for uncoated sheets and for picking the top liner of uncoated paperboard is becoming more common. Besides the K and N waxes, there are those put out by the Dennison Manufacturing Company. They are more widely known. Either kind has its advantages. The disadvantage of using these waxes to measure a small change in the bonding force is that they are not sensitive enough.

In contrast to the tests in which the bonding between plies is measured normal to the surface of the sheet, there are tests which measure the force required to tear plies apart. The latter kind of test is the one more usually used. Courtney and Wakefield(16) have analyzed the problems in connection with the tearing split of plastic materials cemented together with adhesives, and give a good discussion of the tests for measuring the bonding between two plies of plastic materials. They have developed a tester for measuring the force required to tear two sheets apart. A constant speed of separation of the plies was assured by the use of a constant speed motor. The force required was transmitted by means of a calibrated spring, and the extension of this spring served as a means of moving a recording pen over a sheet of coördinate paper. The result was a curve relating the stress and strain. However, the authors were not certain as to the interpretation of these curves. For their work they used the maximum value, but they recognized the possibility of using the area under the curve as a more valuable measure of the bonding force. For the most part, their forces increased linearly up to the value at which the initial tear started and then remained constant throughout the tear. This type of force yields a very simple curve. On the other hand, they obtained some very erratic curves.

Forman(17) copied this tester for the purpose of measuring the bonding strength of different adhesives. He used the maximum values obtained in order to evaluate his procedures and materials. His tester was used in a portion of the present investigation. The modified tester is described in detail and illustrated in Forman's thesis.

The Thwing-Albert Instrument Company markets a tester for measuring the adhesiveness of gummed tape. It is called the McLaurin gummed tape tester(18). It measures the integrated force required to remove the gummed tape from a standard paper after it has been applied to the paper according to a standard procedure.

The first study of any of the factors affecting the bonding between plies of a multi-ply sheet was carried out by Doughty and Baird(19). This was a result of the work of Doughty(1,2) on the effect of wet-pressing on the characteristics of single sheets.

In their investigation, Doughty and Baird studied the effect of wet-pressing on the bonding between plies in a two-ply sheet. The work was exploratory in nature, and they expressed considerable uncertainty as to the interpretation of their results. They made sheets from "slightly beaten" unbleached sulfite, pressed them at different pressures ("pressing pressure"), and subsequently pressed the single sheets together at various pressures("joining pressure") to form two-ply sheets. They tested these sheets for the bonding between plies by tearing them apart and measuring the force required with a triple beam balance. The split, both inside the single sheet and between the two sheets, was started by means of a strip of wax paper inserted during the sheetmaking process. It would have been preferable to use a thin sheet of tissue instead of wax paper in order to eliminate the edge effect as much as possible. One half of the sheet to be split was placed on a hook on the balance and the other half held in the fingers. The tension on the sheet was increased until the tear proceeded at a uniform rate. The reading obtained from the balance indicated the force required to split the 15mm.-wide strip used.

The forces encountered were between 0 and 39 grams. They found that the intraweb(within a single sheet) bonding remained the same for wet-pressing pressures between 0 and 500 pounds per square inch, and that the interweb(between sheets) bonding was always less than the intraweb bonding. It is to be believed that they encountered difficulties in splitting the single sheets, especially if they were at all thin(weight and caliper were not noted), for any representative distance.

The values that they found for commercial boards were much higher than those that they obtained with their experimental sheets. They attributed this to the differences in weight and furnish. The differences in the bonding values are probably due primarily to differences in the couching operations and the amount of beating of the stocks. A criticism of their procedure of pressing the sheets separately before joining them could be made. It would have been better to couch them from the wire, one on the other, as done on a cylinder machine, if the results obtained are to be compared to those obtained using commercial boards.

The authors recognized a disadvantage in measuring the bonding by means of a tearing split. "It is recognized that the relation between the force applied to the ends of the strips in the test method used and the actual tensile strength of the intraweb and interweb bond is conditioned by the angle of separation of the members at the point of contact, and therefore by the thickness and modulus of flexural rigidity of the members separated." It is obvious that this condition exists whenever any two plastic layers are separated in this manner. The perpendicular bonding tests do not have this disadvantage, but the effect of the adhesive used must be taken into consideration. It is reasonable to expect, however, that under similar conditions either test can be used quite well, and that they will indicate changes in the bonding caused by changes in the method of preparation of the sheets.

Doughty and Baird concluded that: (a) The intraweb strength is constant with changing wet-pressing; (b) the interweb strength is greatest when the pressing pressure is lowest and the joining pressure is highest; and (c) to secure good interweb strength, the joining pressure must be higher than the pressing pressure.

Brax(20) is the only other investigator who has studied factors affecting the bonding between plies. He made sheets composed of two plies and measured the bonding by tearing the plies apart. He used groundwood and sulfite sheets. He varied the position of the plies in the sheet(top or bottom) as well as the amount of beating of the stocks. Included in the Finnish article are pictures showing the splitting of tightly bound and loosely bound two-ply sheets. The following is the English summary at the end of the article:

"...Sheets made of fiber material in different stages of wetness and beating were joined together according to methods used in mill production. The cohesive power was measured in grams per centimeter of sheet width....

"(1) The felting possibilities of a paper sheet consisting of two different fiber layers are greater the higher the beating degree of the fiber material. The absolute felting possibilities of the cellulose fiber are greater than those of the mechanical pulp fibers, but the longitudinal splitting resistance of the former, in higher beating degrees, shows a declining or slightly rising tendency, while for mechanical pulp in similar beating degrees, there is a distinctly rising tendency.

"(2) The beating degree of the lower sheet exerts a greater effect on the felting possibilities than does that of the upper sheet. With regard to the quality of the fiber, the relative cohesive power is independent of which layer contains fibers with the greatest felting possibilities. The upper sheet tends to increase the cohesive power only in higher beating degrees.

"(3) In order to reduce the water content, the fiber material of the lower sheet has to be more rough fibrated than that of the upper sheet.

"(4) The splitting danger is greater the smaller the cohesive power of the two layers. It is impossible to increase this however merely by raising the beating degree, because in this way the elimination of water would be difficult and the splitting risk consequently increase. The felting property should be facilitated either by mixing a quantity of cellulose fiber of a suitable beating degree with the mechanical fibers, or by arranging, if possible, the sheet on the wet cylinders in such a way that the fibers on the joining surface are beaten to the highest efficient degree and those on the outer side of the sheet less highly beaten. For this reason, the most practical combination method for machines making duplex products is to take up one of the layers on the wet cylinders.

"(5) If in the two sheet layers there is a great difference in the beating degree of the fiber material, the product does not remain flat in the storing room, but is curving, being largely caused by the cellulose fibers.

"(6) Changes in the rate of acidity, restricted within the usual limits, does not largely affect the felting possibilities. A more alkaline fiber material gives somewhat greater possibilities in this respect."

Jeitteles(21) made a study of the effect of increasing the number of plies for the same thickness and weight of laminated board. He found that the greater the number of plies used, the greater the strength. This means that by using thinner plies a lighter weight sheet can be used, or by using thinner plies a stronger sheet will be obtained for the same weight. This work was done on heavy pasted board and not on the typical multi-ply board.

Brax(20) also discussed the felting of fibers in paper, pointing out the effect of such factors as calendering at unsuitable moisture contents, compactness of the surfaces being joined, and processes which raise the density of the sheet. He recognized either a physical or a chemical phenomenon, or both, as causing felting. He ascribed the increase in bonding with beating to the formation and mutual attachment of fine branches of fibers. For the chemical type of felting he postulated the absorption of the finer parts of the surrounding fibers by the hydrated surface of the cellulose fiber, but maintained that fibrillation increased bonding chiefly because of mechanical effects.

Brax stated that the moisture content of the sheets being joined affected the felting together of two plies, that dry sheets do not adhere and that the felting begins to decrease if the moisture content of the sheet drops below 70 per cent. These findings he ascribed to purely mechanical phenomena. On the other hand, if the sheets are too wet (above 90 per cent water), the plies will not bond since, if a large amount of water is removed rapidly, the strength of adherence possible between plies and fibers is reduced and the sheet is often crushed. The shorter the fibers and the more highly beaten the stock, the greater the effect of an excess of water.

Brax made his study using two-ply sheets, weighing about 100 grams per square meter (about 72 pounds on a 25 in. x 40 in.--500 basis), the lower ply of which was not pressed after it was formed, while the top ply was pressed with a metal roll. The two plies were joined by pressing between flat plates for five minutes at a pressure of about 70 pounds per square inch. Strips 15 mm. wide were torn apart on a Schopper tensile tester.

EXPERIMENTAL PROCEDURES

PREPARATION OF STOCKS

A. Unbleached Sulfite Pulp

A large portion of the experiments were carried out on unbleached sulfite pulp. At the beginning of the investigation, a large supply of dry West Coast unbleached sulfite was obtained and stored at 70° F. and at a relative humidity of 65 per cent and was beaten as needed. For many of the experiments enough stock was needed so that it was necessary to use the five-pound Valley beater for the beating operation. The stock was beaten at a consistency of about two and one-half per cent with a moderate weight on the bedplate, e.g., ten pounds, to the freeness desired in the particular experiment being carried out. The freeness was determined at 20° C., using the Schopper-Riegler freeness tester (22), and throughout this work it is reported as the cc. volume of quick draining water. At other times, only a small amount of stock was desired; therefore, this was beaten at a consistency of about two per cent in the 1 1/2-pound Valley beater with 4500 grams on the balanced bedplate.

After beating the stock was thickened by draining off the water and was stored in stoneware crocks until required. If the time required to make the series of sheets for the experiment was more than one hour, the stock was allowed to stand overnight or longer, in order to reduce the effect of the stock changes during the time the sheets were being made. The final freeness was determined just before the stock was made into sheets. Care was taken to insure uniform stock throughout the course of any one experiment, and as nearly as possible between experiments, when this was desirable.

B. News-unbleached Sulfite Pulp

In order to secure a low grade stock, comparable to chip in commercial work but more easily duplicated, old newspapers were used. The clay-free portions of January 1938 issues of the New York Times were slushed in the Valley beater together with 10 or 20 per cent West Coast unbleached sulfite until completely defibered. If this stock was not to be used within a short time, it was thickened and stored as in the case of the unbleached sulfite.

C. Bleached Sulfite Pulp

The bleached sulfite used for measuring the effect of the number of plies on the strength properties of multiply board was West Coast bleached sulfite, beaten at a consistency of about three per cent in the 1 1/2-pound Valley beater with 6750 grams on the balanced bedplate.

The pulp used for the beater run on the bleached sulfite was obtained from a New England mill and was beaten at a consistency of 2.7 per cent in the five-pound Valley beater with 20 pounds on the balanced bedplate.

D. Unbleached Kraft Pulp

The unbleached kraft pulp was a very free stock prepared in commercial equipment and used as the top liner on a cylinder machine making 30-point kraft-lined chipboard.

E. Chip Stock

The chip stock used was a commercial product, prepared with a beater and a jordan, and was used for the filler of the 30-point kraft-lined chip mentioned above. This stock, as well as the following two, was used in only one experiment, namely, the effect of the number of plies on the strength of the multi-ply sheet.

F. Kraft-sulfite Waste Stock

The kraft-sulfite waste stock was the back liner stock for the 30-point kraft-lined chipboard.

G. Groundwood-sulfite Stock.

The groundwood-sulfite stock was a fifty-fifty mixture of wet-lap groundwood for book paper and West Coast unbleached sulfite. The two pulps were defibered and mixed by slushing in the 1 1/2-pound Valley beater for 40 minutes.

SHEETMAKING

A. Preliminary Work

The preliminary work was carried out on the Williams sheetmaking equipment and, as far as studied, it was satisfactory. However, the range of couching pressures available was not wide enough and the process of building up the multi-ply sheets was relatively slow. Consequently, the Noble and Wood sheetmaking apparatus was used, and all the work reported in this investigation was carried out with this equipment.

B. The Noble and Wood Equipment

The Noble and Wood equipment is a relatively new unit which has several advantages over other existing equipment for making handsheets. It allows sheets to be made under conditions which resemble more closely machine operation and even give a slight machine direction, or grain, to the sheet. Its operation is simple and rapid, and sheets can be readily duplicated on it. With the additional white water system that is available, it is possible to carry out studies in which it is necessary to use white water in order to secure the proper results.

The apparatus and its use are described in an article by Coghill (23). His recommended procedures were not followed exactly in this investigation, but the modified procedures will be found below. The white water return system was not generally used; in all cases the sheets were drained by means of the vacuum pump rather than by the barometric leg. In most of the work, five sheets were made for each set of experimental conditions.

C. Dilution of Stock

Instead of using the proportioning system of the equipment, it was found more convenient to prepare a large amount of stock and to measure out the desired amount. The thick stocks, prepared as described above, were diluted to a consistency of about 0.8 per cent and kept in uniform suspension by means of a Lightnin' mixer. The freeness of the stock was determined after this dilution.

D. Forming the Sheet

The stock was further diluted in the sheet mold with enough water to fill the mold to the upper mark; therefore, the final consistency of the stock in the mold was dependent on the weight of the sheet being made. An exception to this occurred when very slow stock was used, when, in order to secure drainage in a reasonable time, less water was used in the sheet mold. The stock was agitated in the mold by means of a perforated plunger-type stirrer. The water was drained from the mold by means of a vacuum pump capable of maintaining a vacuum of more than 27 inches of mercury. The sheet was formed on a 65 by 70 mesh wire.

E. Couching the Sheet

After the sheet was formed, the wire was removed from the mold and placed, sheet down, on a felt for the couching operation. The sheet was couched from the wire to a piece of machine press felt, placed inside the regular Noble and Wood press felt, by passing the two felts, the sheet, and the wire between the weighted press rolls. It was observed that if too high a couching pressure was used, the sheet would not leave the wire. This condition existed for conditions above approximately 25 pounds per linear inch, although this value depended somewhat on the nature of the stock.

A multi-ply sheet was built up by couching one sheet upon another. One sheet was couched on the felt, the next one on that sheet, etc., until the required number of plies was obtained. To help start the split, a narrow strip of tissue or wax paper was inserted along the back edge of the sheet between the plies that were to be split later.

F. Operation and Adjustment of Press Rolls

The correct adjustment and operation of the press rolls is important and must be carried out properly. Care should always be taken to see that the clearance between the rolls is just enough so that when the sheet and wire begin to go through the rolls, the weighted lever arms rise off their supports a small distance. As the thickness of the sheet is increased, the clearance between the rolls must be increased; as the amount of pressure is increased, the clearance between the rolls must be decreased.

When the clearance was so adjusted and the top roll balanced, it was possible to determine directly from the position of the weights on the arms the amount of force acting on each journal of the top roll (23). When the sliding weights were at the foremost and least effective position, the top roll was supposed to exert zero weight on the journals, i.e., the roll was balanced. However, this was not the case, for it was necessary to suspend a weight of 10 pounds from the negative end of each arm in order to balance the top roll. Under these conditions the possible range was between 0 and 600 pounds on each end journal of the top roll, permitting a force up to 1200 pounds to act on the material between the rolls. Since the length of the zone of contact was taken to be the width of the wire, i.e., nine inches, the maximum force obtainable when the clearances were set as described was 133.3 pounds per linear inch. With insufficient clearance, a force of 150 pounds per inch was obtained in some of the experiments.

G. Pressing the Sheet

After the required number of plies had been built up, the multi-ply sheet was given a final pass through the press rolls, with the wire on top of the sheet. Pressing with the wire helped prevent the crushing of the sheet, especially when high pressures were used. The correct adjustment of the rolls was also necessary to prevent crushing. The amount of pressure used for the final pressing was varied, although much of the work was carried out with a final pressure of 66.7 pounds per inch.

H. Moisture Content

The moisture content of the sheets after couching or pressing was determined by the use of a strip, usually one-half to five-eighths of an inch wide, taken about one-half of an inch from the edge of the sheet and along an edge parallel to the motion of the sheet through the rolls. These strips were dried in an oven at 105° C.

I. Drying the Sheet

The sheets were dried on the rotating drier supplied with the Noble and Wood apparatus at a temperature controlled between 102 and 105° C. The wire was removed from a heavy sheet before drying, whereas the light single sheets used in some experiments were dried in contact with the wire. In any series of experiments, all sheets were dried as nearly as possible to the same extent; in every case they were dried until they came from the drier without a pronounced curl. The curling of the sheets as the result of seasoning could be reduced by giving the sheets three to five passes through the drier, rotating the sheets through an angle of 90° each time, instead of drying them in one pass.

J. Calendering the Sheet

In certain experiments the sheets were calendered, using the Noble and Wood press rolls, although the rolls could only be used cold. The rolls had to be carefully cleaned and dried before calendering. In the calendering operation, the clearance between rolls was reduced to zero, i.e., the rolls were brought into contact, the weights placed in the desired position, and the sheet passed between the rolls with first one side up and then the other and with the same edge leading each time (usually the one opposite the edge containing the strip separating the plies). Both the number of passes at a given pressure and the pressure for a given number of passes were varied.

TESTING THE SHEETS

A. Seasoning

All sheets were seasoned at 70° F. and 65 per cent relative humidity for at least 16 hours and tested under these conditions, with the exception of the experiment in which the effect of drying was studied. The procedure used in this case will be noted later.

B. Basis Weight

The weight of the sheets was determined by weighing 7 1/2 in. by 7 1/2 in. sheets on a large basis weight scale (24), reading the weight in pounds for 500 sheets the size of those weighed, as recommended by TAPPI Standard Method T 410 m-36. From this value, the basis weight used for all work reported, even for the thin single sheets unless otherwise indicated, namely, the usual board basis (weight in pounds per thousand square feet), was calculated. This basis weight multiplied by three gives the weight in terms of a 24 in. by 36 in.--500 basis.

C. Caliper

The thickness of all sheets was determined with the Cady caliper. The values reported are in terms of points or thousandths of an inch.

D. Bursting Strength

The bursting strength test was carried out according to Institute Method 510, which is also TAPPI Standard Method T 403 m-36. The large Perkins Mullen tester was used for most of the sheets, the smaller tester being used only for the thin single sheets. For the heavier sheets, an average of 20 tests, and for the lighter sheets, an average of 15 tests was usually reported. Values are tabulated as pounds per square inch per hundred pounds.

E. Tearing Strength

The tearing strength of all sheets was measured on the Elmendorf tear tester, in most cases according to Institute Method 512 and TAPPI Standard Method T 414 m-37, but in some cases it was necessary to increase the capacity of the tester by the use of the supplementary weight provided with the tester. This procedure has been described by Carson and Snyder (25).

It was observed that, when the heavier sheets were torn, even solid single sheets tended to split inside the sheet, thus giving too high values. The tearing results are reported as tear factor, i.e., tear, in grams for sixteen sheets divided by the basis weight.

F. Tensile Strength and Stretch

Tensile and stretch tests were carried out on the Amthor tensile tester, which is similar to the Schopper tensile tester, the major difference being due to the higher rate of loading used with the Amthor tester. Tests were usually carried out on strips 15 mm. wide and 3 in. long. The tensile results are tabulated in terms of pounds force per hundred pounds, the stretch as per cent of the original length.

G. Suvant Stiffness

The measurement of stiffness with the Suvant tester (sometimes called the Smith-Tabor stiffness (26)) has been described and the problems involved analyzed in the Instrumentation Studies carried out by The Institute of Paper Chemistry (27). The values reported are in terms of units per hundred pounds.

H. Riehle Stiffness

Riehle stiffness is different from that measured by the Suvant instrument, for it represents the resistance to crushing rather than the resistance to bending. It was measured on strips one-half inch wide and two inches long, with the crushing force being applied against the long edge of the sheet held in the form of a cylinder. The values reported are in terms of pounds force per hundred pounds.

I. M.I.T. Folding Endurance

The folding endurance was measured in only a few cases, and then mostly for thin single sheets, although the test can be used for board. The test was carried out according to Institute Method 513B, and the results are reported directly as the average of the tests (usually ten).

J. Cobb Size Test

The Cobb size test measures the amount of liquid absorbed by a given area of the sheet in a given time (28, 29). Although it was used only in the preliminary work of this investigation, and none of the results are reported, it is mentioned here, because it is probably the best test for measuring the degree of sizing of board. This test should be used in any sizing study of handmade board, for it was found to be quite satisfactory the few times it was used in the present investigation.

K. Dennison Pick Test

The Dennison pick test was carried out in some of the first experiments, but none of the results are reported because the test was not sensitive enough and the pick values were all between 12 and 15. The pick value was taken to be the number designating the wax which just failed to pick the top liner from the inner liner (15); waxes with greater adhesiveness either caused the top liner to lift a little from the inner liner without breaking or to be picked off completely. Since this test was not sensitive enough for the present work, it was not used to any appreciable extent, but more applicable tests were worked out.

L. Tearing-type Splitting Tests

(a) The Forman tester

The tester devised by Courtney and Wakefield (16), as modified and used by Forman (17), was reconstructed and used in a part of this investigation. Since the test could be made more accurate by using the proper strength springs, several different springs were made and calibrated. A further improvement could be made if the recording part of the instrument were built larger so that the spring would have a greater extension, thus increasing the amount of pen movement for a given change in the splitting force. It must be remembered that in this test, as in all tearing-type splitting tests, the stiffness and the thickness of the ply being torn off affect the results. Doughty and Baird (19) have also pointed out this fact.

On the whole, this tester worked well mechanically and gave moderately satisfactory results, but the difficulty of determining just how to use the results was not overcome. It may be said that the tester gave too much information. The magnitude of the force at any time during the splitting, the initial splitting force, and the maximum instantaneous force required over a given length could be determined from the curve. By integrating the curve, carried out by determining the area under it, the integrated or average force required to split a given area of the sheet can be determined.

It was found that the initial splitting value was not very reproducible, due to variations in the bonding brought about by the inserted strip used to start the split. In any test measuring the tearing split, the length of the split must be sufficient to make negligible any edge effects that are introduced in starting the split. The maximum and average forces are the better means of measuring the bonding with this instrument. However, in order to secure good results, it was necessary to run several tests (about ten) for each set of experimental conditions. This required considerable time, especially in determining the integrated force. The results obtained with this tester may be obtained by the use of the tensile tester and the tear tester in combination, from which the readings may be obtained directly without the need of converting chart readings to force readings.

Figures 1-3 illustrate three typical types of curves obtained with the Forman tester on multi-ply sheets. Figure 2 shows the type most usually obtained, while Figure 3 represents the least usual type of curve. Figure 1 represents a tearing force which increases until the split begins and then remains constant throughout the split. Figure 2 illustrates a force that increases as the tear proceeds.

Figure 3 represents the results obtained when the sheet has weak spots, such as blisters.

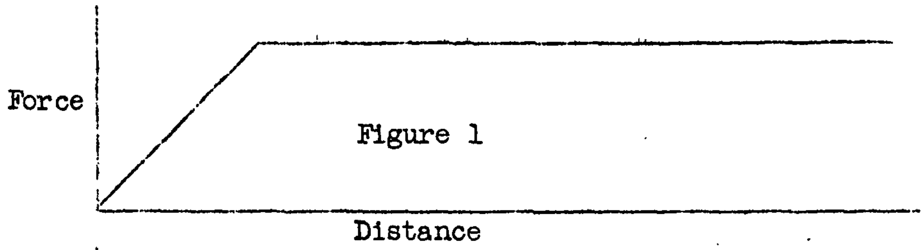


Figure 1

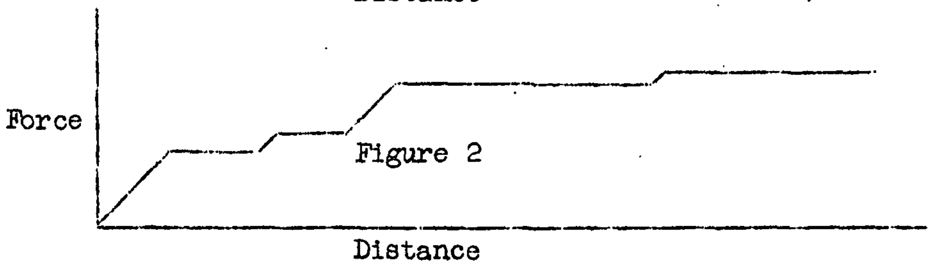


Figure 2

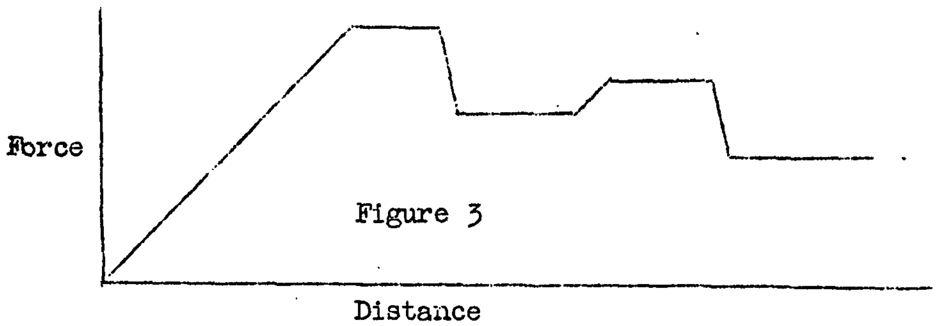


Figure 3

(b) Tensile tester

A Schopper tensile tester was used that would measure a force from 0 to 1000 grams, which was the range required in this work. It is a modification of Instrument Number 528 as described in the Schopper catalog (30). The force was supplied by gravity acting on a falling piston. The tester was suitable for splitting a strip 15 mm. wide and 2 1/2 in. long. The split was started, the two sides of the strip fastened into the clamps, and the piston released. The initial tensile force required to start the split, as well as the maximum force required in the 2 1/2 inches torn, could be determined, but the tester was not satisfactory, principally because it was not sensitive enough. The percentage of change in the values was not as great as that of the values for the integrated force obtained with the tear tester, and the variations for any one sheet were quite large. A larger area of splitting surface was desirable.

(c) Tear tester

The method of measuring the integrated force required to split a definite area of the sheet with the tear tester was simple. Strips one inch wide and with a splitting length up to 3 1/2 inches were used. The split was started, and the heavy side of the sheet was clamped in the front jaw of the Elmendorf tear tester, with the long axis of the sheet perpendicular to the plane of motion of the sector, i.e., the sheet extended to the front. The other side of the sheet was held in the fingers, the pendulum released, and the sheet split apart. During the splitting, it was advantageous to allow the wrist to turn while the arm was held stationary, so that the sheet would not tear off to the side instead of splitting the whole length of the strip. Due to the simplicity of the test and the possibility of getting consistent results, this test is recommended for all bonding measurements when it is desired to measure the bonding force between any two given plies and not the weakest force in the sheet.

M. Perpendicular Bonding Test

The perpendicular bonding test was developed to measure the tensile force required to split sheets when the force is applied normal to the surface of the sheet. Whether a solid or multi-ply sheet is used, this test will measure the weakest point in that sheet.

The test samples of the sheets, approximately 1 1/4 by 1 1/4 inches, were cemented, either with an animal glue or 40 per cent sodium silicate, between two blocks of Western white pine exactly one inch square and about three-quarters of an inch thick. After the sheet was cemented between the blocks, the assembly was pressed firmly together by hand for a few seconds and then allowed to season overnight, not so much to set the adhesive as to allow the excess moisture to evaporate from the sheet. The edges of the sheet were trimmed off flush with the blocks, thus giving a paper area of exactly one square inch. A larger area would be better if equipment were available for pulling the larger sheet apart.

Wood screws, the heads removed, slotted, and a copper strip soldered into the slot, were then screwed into each of the blocks, the strips of copper fastened into the clamps of the Amthor tensile tester, and the assembly subjected to an increasing force. The failure always occurred in the sheet when the cementing was carried out properly.

Originally the blocks were cut from a 3/4-inch board that had been planed and sanded. It was necessary that the surface of the blocks be flat in order to secure a good bond between the paper and the wood without using an excessive amount of adhesive. In crder to facilitate the insertion of the clamping strips and to insure the application of the force normal to the surface of the blocks and paper, holes were drilled with a drill press in the back of the blocks, perpendicular to the blocks. The blocks were reused several times, being resurfaced each time by peeling off most of the paper and rubbing the blocks with a circular motion over a flat sheet of sandpaper, keeping the surface of the blocks flush against the sandpaper.

At first the procedure was to cut the sheets into one-inch squares and to use blocks somewhat larger. This was not satisfactory, because if enough adhesive was used to give a good bond between the paper and the wood, it would be squeezed from between them and seal the edge of the sheet so that too high a value would be obtained, but if less adhesive was used, the bond would not be adequate. Therefore, the blocks were made the desired size and the sheets larger than the blocks.

The adhesive to be used depended on the nature of the sheet. If it was tightly bound together, animal glue was used in order to obtain a strong enough bond between the sheet and the blocks and, since such sheets were relatively nonporous, the glue did not penetrate very far into the sheet. Most of the work on two-ply sheets was carried out on relatively thick sheets so that the glue did not penetrate far enough into even the most porous sheets to mask the boundary between plies.

However, with thin single sheets, the glue did penetrate the sheet and bridge over from one block to the other; the result was too high a force to pull the sheet apart. Therefore, for this type of test, sodium silicate was used as the adhesive, since it was found that the silicate did not penetrate even the most porous sheets. This nonpenetration of silicate has also been observed by other investigators (9,10).

Adhesives made by compounding waxes were also used. However, they were difficult to apply and did not have sufficient strength to pull the more tightly bound sheets apart. For all normal commercial sheets, silicate is the most suitable adhesive.

The glue used was Peter Cooper's number 35 dry glue. It was prepared by soaking 400 grams in 1450 cc. of cold tap water for 4 hours, then heating to 60° C., holding the mixture at this temperature for 2 hours, and finally adding 30 cc. of glycerine. The glue was reheated to 45° C., and applied by brushing it on the blocks.

The silicate was used without any pretreatment. It was brushed on the blocks, the excess wiped off, and the sheet placed between the two silicated surfaces. It was not necessary to press either the glue or the silicate, other than squeezing it firmly together by hand.

The following list summarizes the units in which the results for each kind of test are reported:

Weight......................Pounds per thousand square feet
Caliper.....................Points, or thousandths of an inch
Mullen......................Pounds per sq.in. per hundred pounds
Tear........................Tear Factor
Tensile.....................Pounds per hundred pounds
Stretch.....................Per cent
Suvant Stiffness............Units per hundred pounds
Riehle Stiffness............Pounds per hundred pounds
M.I.T. Fold.................Number of double folds
Tear Split..................Grams force for area tested
Forman Test.................Grams force for strip tested
Tensile Split...............Grams force for 15 mm.-wide strip
Perpendicular Bonding......Pounds per square inch

PRESENTATION AND DISCUSSION OF RESULTS

In any study related to papermaking requiring the use of handsheets, it is necessary that three conditions be fulfilled. First, different handsheets made under the same conditions must possess the same properties. Whether the properties in question are just weight and caliper, or strength, or even resistance to liquid penetration, it is necessary that each sheet be the same in these respects, within reasonable limits. Secondly, handsheets made under different conditions must be different. The final condition which must be fulfilled is that the handsheets have a constant relation to machine-made sheets. It is desirable that this relation be close, but to study only the effect of changes in procedure, it need not be very close. In a study such as the present one, the primary requirement is that the properties of the handsheets be reproducible, although the approximate relation of the handsheets to machine-made sheets should be known.

Duplication of Handsheets

It was found that the method of sheetmaking used was quite suitable for preparing handsheets that were relatively constant under the same conditions and different under different conditions. For accuracy, five 8 inch by 8 inch sheets were usually made for each set of conditions. They were trimmed to 7 1/2 by 7 1/2 inches for testing and as many tests were run as the area of the sheet would permit.

Table I shows the reproducibility of results as they were obtained on a set of five handsheets, with the tests distributed uniformly over the sheets. These sheets were made from West Coast unbleached sulfite having a freeness of 620. They were two-ply sheets, representative of much of the work carried out, couched with 3.3 pounds per linear inch and pressed with a force of 66.7 pounds per linear inch on the top press roll. After drying at 105° C., they were calendered, using four passes with a force of 93.7 pounds per inch on the roll. The basis weight of the sheets was 62.4 pounds per thousand square feet; the caliper was 14.9 points.

The following figures are the average percentage deviations from the mean for the tests given in Table I.

(a)	Mullen..................	±4.1%
(b)	Tear....................	±4.3%
(c)	Riehle..................	±6.6%
(d)	Tensile.................	±4.5%
(e)	Stretch.................	±12.5%
(f)	Suvant..................	±3.0%
(g)	Tearing Split...........	±7.3%
(h)	Perpendicular Bonding....	±27.4%

The perpendicular bonding and the stretch tests are the only ones that vary widely. Such wide variations in the perpendicular bonding tests are due more to the nature of the sheet than to the test, as will be shown later in connection with the use of this test on machine-made board. To reduce the effect of such variations and to obtain a reasonable average result, it is necessary to make at least ten tests on handsheets.

TABLE I

REPRODUCIBILITY OF TESTS ON HANDSHEETS

Mullen Tests	Riehle Tests	Tensile Tests	Stretch Tests	Suvant Tests	Perpendicular Bond.	Tear Split	Tear Tests
214	38.0	55.7	4.75	37.1	36.1	19.8	35.7
219	37.5	57.0	3.05	38.5	23.6	20.8	32.1
211	39.5	53.6	2.60	37.2	25.0	28.2	31.1
206	35.5	50.7	3.40	41.1	21.9	21.9	33.2
215	33.5	50.0	3.65	37.9	33.5	22.1	31.1
201	36.5	55.8	2.90		20.7	21.2	32.7
204	31.5	50.8	2.90		44.5	20.0	31.1
206	32.5	53.8	3.05		44.9	22.4	32.7
205	31.5	58.9	3.00		35.0	21.8	32.8
205	35.5	52.0	3.25		57.7	25.1	37.1
199							33.9
201							33.7
226							30.4
197							31.2
201							33.9
231							37.5
224							34.9
205							33.3
228							33.3
201							33.9
210	35.2	53.8	3.26	38.4	34.3	22.3	33.0

<u>Relation Between Handmade and Machine-made Board</u>

In order to establish the relation between the strength properties of board made from handsheets and that made from commercial stock on a cylinder machine, handsheets were made from the stock being run on a six-cylinder machine at a local board mill and were compared with the uncalendered board made from the same stock on the machine. The stock was taken from the overflow at the regulating box and made into handsheets as soon as possible. Fresh water was used for its dilution in making handsheets instead of white water as on the machine; also, the handsheets were formed at consistencies different from those used on the machine.

The handsheets were couched with a force of 23.3 pounds per inch and pressed at 33.3 pounds per inch. The weight of each ply in the machine sheet was matched in the handsheets and the pressing was carried out to give the same over-all caliper. It would have been better to use a lower couching pressure and a higher pressing pressure in order to secure better bonding. Table II summarizes the composition of the machine sheet.

TABLE II

COMPOSITION OF 30-POINT KRAFT-LINED CHIP

Stock	
Top liner, kraft, freeness	810
Filler, chip, freeness	430
Back liner, kraft-sulfite waste, freeness	530
Caliper	
Over-all	28.5
Top liner	3.8
Back liner	5.5
Filler, each ply	4.8

Basis Weight	
Over-all	85.0
Top liner	16.9
Back liner	14.9
Filler, each ply	14.3

Table III shows the relation between the handsheets and the commercial sheet.

TABLE III

RELATION BETWEEN HANDMADE AND MACHINE-MADE SHEETS

	Handsheets	Machine Sheet
Weight	88.7	85.0
Caliper	29.0	28.5
Mullen	179	161
Tear	9.7	6.4'
M.I.T. fold	664	240"
Riehle	40.7	49.6"
Tensile	53.6	56.8"
Tear Split	18.4	34.3"
Perpendicular Bonding	21.4	32.8

' In direction only
" Av. in and across

This comparison shows that the strength of handsheets made in this manner approximates that of a machine-made sheet, particularly in the case of the bursting strength. When it is considered that the tear data reported for the machine sheet are for the tear in the machine direction only, for the sheet would not tear across the grain, the difference in the tear values is reasonable. The folding endurances are quite different when the average of the cross- and in-machine directions for the machine sheet is considered, but the cross-machine direction gave a value of 458, which is nearer that of the handsheets. The largest variations are in the two bonding tests, but had a lower couching pressure been used in the preparation of the handsheets, the bonding in the handsheets would have been increased. In all the perpendicular bonding tests, the sheet split under the top liner because of the high freeness of the top liner stock; a very free stock gives a poor bond.

Evaluation of Bonding Tests

The tests that might be used for measuring the bonding between plies in a multi-ply sheet were evaluated and some of the effects introduced by the use of adhesive in the perpendicular bonding test were also determined.

Comparison of Bonding Tests--Changes in Bonding Produced by Pressing

Table IV and Figure 4 show the relation between the different tests for one experiment in which the final pressure was varied. The sheets used for the comparison were two-ply sheets of unbleached sulfite with a freeness of 595. The sheets were couched with a force of 3.3 pounds per inch, pressed with different pressures as noted in the table, and dried at 105° C.

The strips used for the tearing split with the tear tester were 1 inch wide and had a splitting length of 3 inches. Those used for the Forman tester were 2 inches wide and had a tearing length of 3 inches. The strips used

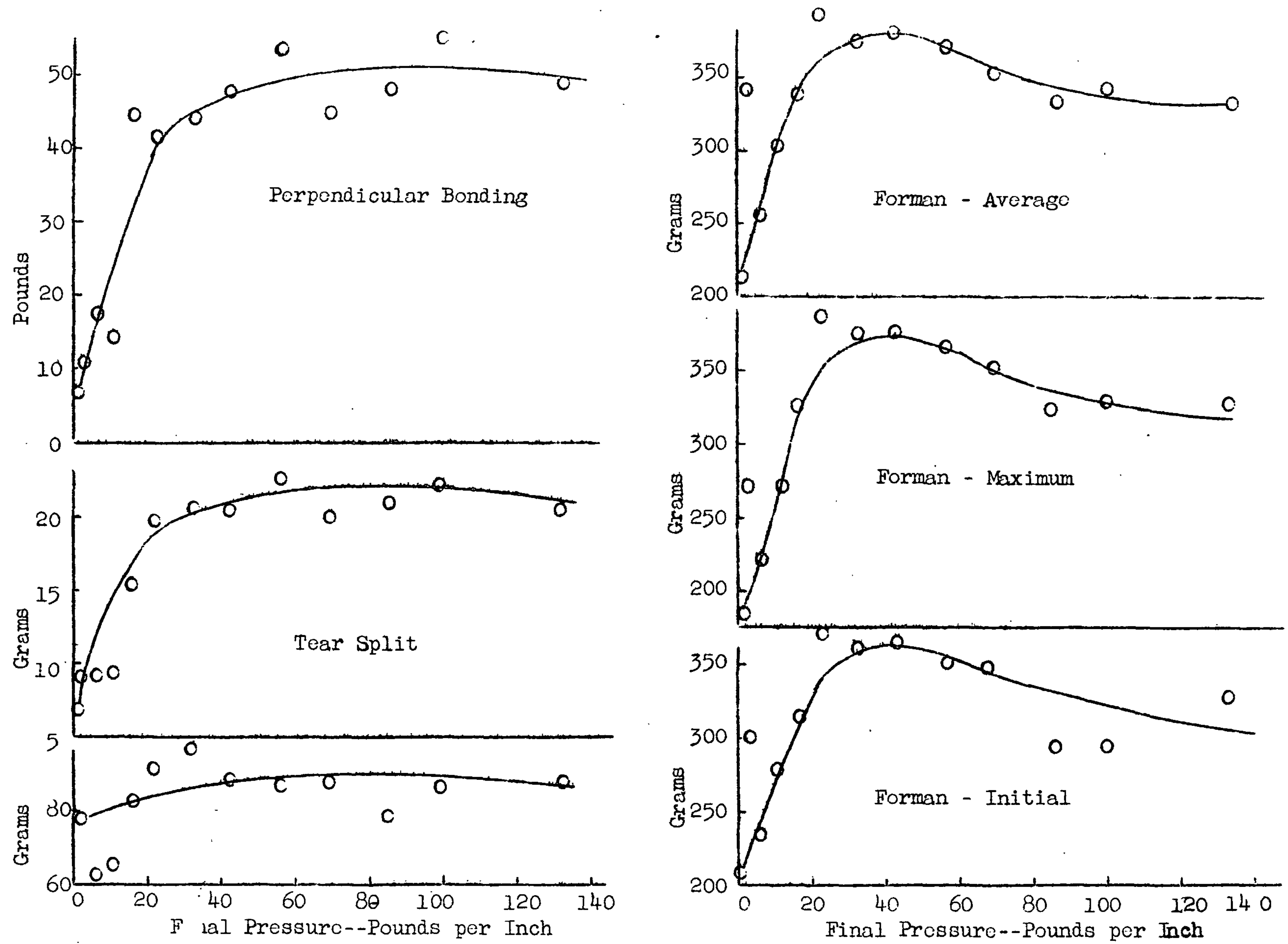


FIGURE 4. EFFECT OF FINAL PRESSING ON BONDING.

on the tensile tester were 15 mm. wide with a tearing length of 2 1/2 inches. The perpendicular bonding samples were 1 inch square after trimming. Animal glue was used to cement the sheets between the blocks. The forces reported for the tearing-type splitting tests are in grams; those for the perpendicular bonding are in pounds.

TABLE IV

COMPARISON OF BONDING TESTS

Press. lb./in.	Tearing-type Split						Perpen-dicular Bonding
	Tear Tester	Tensile Tester		Forman Tester			
		Initial	Max.	Initial	Max.	Av.	
0.0	6.7	66	76	200	212	176	6.3
3.3	8.9	62	77	299	341	270	10.7
6.7	8.9	57	61	230	254	218	17.5
11.7	9.3	58	64	277	301	268	14.2
16.7	15.2	71	82	312	339	322	44.8
23.3	19.5	77	80	371	393	385	41.7
33.3	20.5	68	96	359	374	372	44.7
43.3	20.4	62	87	362	381	374	46.0
56.7	22.3	78	86	348	370	363	53.7
70.0	20.0	84	84	344	352	349	43.0
86.3	21.2	74	79	293	335	324	48.0
100.0	22.1	77	86	293	280	329	50.5
133.3	20.6	72	86	325	332	328	44.1

Deviations in Individual Test Results for Handsheets

Table V shows the individual readings obtained for each type of bonding test on one set of handsheets. Table VI shows the average percentage deviation from the mean value for the series of tests whose averages are reported in Table IV.

TABLE V

VARIATIONS IN INDIVIDUAL TEST VALUES

Tearing-type Split						Perpen-dicular
Tear Tester	Tensile Tester		Forman Tester			
	Initial	Max.	Initial	Max.	Av.	Bonding
17.1	87	87	282	292	288	65.4
19.0	96	96	282	292	288	47.0
23.9	81	85	308	375	362	55.3
24.0	92	92	380	380	380	54.0
22.8	56	101	358	413	380	47.0
25.2	56	86	455	494	487	49.0
20.8	86	86	354	354	354	53.4
21.7	88	88	375	375	375	65.7
24.3	76	76	308	342	333	56.7
24.3	65	68	358	385	380	44.4
22.3	78	86	348	370	363	53.8

TABLE VI

AVERAGE PERCENTAGE DEVIATION OF BONDING TESTS FROM MEAN VALUE

Press. lb./in.	Tearing-type Split						Perpen-dicular
	Tear	Tensile Tester		Forman Tester			
	Tester	Initial	Max.	Initial	Max.	Av.	Bonding
0.0	20.5	36.4	22.9	32.2	32.2	22.6	66.7
3.3	23.0	34.4	23.4	17.5	11.4	13.2	51.6
6.7	28.8	35.1	39.7	15.9	13.9	12.7	53.0
11.7	31.8	29.0	26.0	10.8	15.5	15.1	57.4
16.7	13.6	18.0	9.3	19.5	14.9	14.5	8.5
23.3	4.6	10.4	10.0	17.1	11.1	13.0	19.0
33.3	8.3	14.4	18.1	12.0	10.7	11.1	13.6
43.3	5.1	10.5	8.0	13.5	12.4	12.4	7.7
56.7	9.5	15.0	7.3	11.0	10.9	10.4	10.4
70.0	8.4	12.4	14.0	9.9	8.7	9.2	15.6
86.3	4.8	18.9	13.7	7.3	4.5	4.6	15.3
100.0	7.2	12.5	14.0	19.7	20.6	23.8	9.4
133.3	5.7	9.2	13.2	3.3	7.6	5.4	22.6

It will be observed that, at the lower bonding forces, the tests deviate greatly from the average. This is to be expected because of the inaccuracy with which the scales are read at the lower end and the lack of sensitivity of some of the instruments for low forces. The following list shows the percentage deviation from the mean value which may be expected for each of the bonding tests, both for the whole range of values covered and for the range where the results are more critical:

	Entire Range	Critical Range
Tear Tester...............	13.2%	7.5%
Tensile tester		
Initial...............	19.7%	13.7%
Maximum...............	16.9%	12.0%
Forman tester		
Initial...............	14.6%	12.6%
Maximum...............	12.0%	9.3%
Average...............	12.9%	11.6%
Perpendicular bonding.....	25.4%	13.6%

Deviations in Individual Test Results for Machine-made Board

The applicability of these different tests to machine-made board was also determined. The following list shows the percentage deviation from the mean which may be expected with a machine sheet. The sheet used was calendered 30-point kraft-lined chipboard.

	Mean	Deviation
Tear tester..............	20.5	15.0%
Tensile tester		
Initial................	50	29.0%
Maximum................	130	11.6%
Forman tester		
Initial................	505	22.1%
Maximum................	847	11.5%
Average................	712	9.8%
Perpendicular bonding.....	33.8	8.0%

Table VII shows the results obtained for a series of forty perpendicular bonding tests on the machine-made sheet mentioned above. The tests were run on samples taken one after the other in a line along the machine direction of the sheet in order to reduce the effect of variations in the sheet to a minimum. Glue was used as the adhesive. The results show the accuracy which may be expected when the sheet is as uniform as possible.

TABLE VII

PERPENDICULAR BONDING TESTS ON MACHINE-MADE SHEET

Test No.	lb./in.^{2}	Av.	Test No.	lb./in.^{2}	Av.
1	37.5		21	37.7	
2	36.0		22	34.9	
3	35.2		23	33.3	
4	38.2		24	39.7	
5	32.4	35.8	25	32.9	34.2
6	31.6		26	31.6	
7	30.3		27	37.6	
8	33.0		28	37.2	
9	37.5		29	35.2	
10	27.5	33.9	30	33.4	34.3
11	33.8		31	32.2	
12	35.1		32	34.3	
13	37.0		33	37.2	
14	34.2		34	32.4	
15	31.9	34.1	35	29.8	34.1
16	37.7		36	31.9	
17	32.5		37	29.4	
18	32.8		38	27.7	
19	34.5		39	27.7	
20	27.3	33.8	40	39.6	33.8

Effect of Adhesive on the Perpendicular Bonding Tests

The effect of the adhesive on the results obtained using the perpendicular bonding test was determined for thin two-ply handsheets, thick two-ply handsheets, and calendered 30-point kraft-lined chipboard. The use of the following adhesives was attempted:

(a) Animal glue, prepared as described on page 35
(b) Sodium silicate, 40 per cent solution
(c) Dennison number 20 pick test wax
(d) Dennison labels, labels glued to block
(e) DuPont Household Cement
(f) Beeswax-gum rosin, 50-50 mixture
(g) Formulated wax
    13 parts carnauba wax
    7 parts beeswax
    8 parts gum rosin
    3 parts castor oil

Of the adhesives used, d, e, f, and g were not sufficiently strong, as applied, to allow the perpendicular bonding test to be carried out on the handsheets; adhesives c, d, e, and f were not used on the machine sheet.

The effect of the time of seasoning after cementing the sheets with silicate and glue was determined, but only two seasoning times were used, one immediately after cementing and the other after 20 hours.

The handsheets designated as "heavy" in Table VIII had a basis weight of 65.0 pounds; those designated as "light" had a basis weight of 16.6 pounds. The calipers were 19.4 and 5.7, respectively. The tearing split was carried out on the heavy and light handsheets, and the splitting forces were 39.3 and 19.4, respectively. The sheets were made from unbleached sulfite stock with a freeness of 620 and were couched, pressed, and dried the same way. (Naturally a longer time was required to dry the heavy sheets.) The machine sheet split under the top liner in all tests. Table VIII summarizes the results obtained.

TABLE VIII

EFFECT OF ADHESIVES ON PERPENDICULAR BONDING TESTS

Adhesive	Handsheets Heavy	Handsheets Light	Machine Sheets
Glue (10 min.)	36.8	----	----
Glue (20 hr.)	93.7	51.9	29.5 28.0
Silicate (10 min.)	39.7	----	----
Silicate (20 hr.)	72.4	67.9	31.2
Dennison wax	85.8	85.1	----
Formulated wax	----	----	34.8

It is apparent from these results that the nature of the adhesive and the method of its application have a marked effect on the perpendicular bonding test. The differences are not due as much to the nature of the adhesive material itself as to the medium containing the adhesive, e.g., water, and the method of preparing the cemented sheets for testing. It is obvious that the time of seasoning after the sheets are cemented between the blocks with an adhesive containing water plays one of the most important roles in the test.

The introduction of water into the sheet makes the time of seasoning important, for the bonding between plies is decreased when the moisture content of the sheet is increased, as will be shown later, It then appears that the chief, if not the only, reason why unseasoned sheets give a much lower test than seasoned ones in the presence of excess moisture in the sheets at the time of testing.

During the seasoning of the block assembly, the increase in the bonding between plies is not due to the distribution of the water throughout the sheet; even with no seasoning period, the moisture has already reached the boundary between plies, since that is the point where the sheet is split by the relatively low force. The major process which causes the increasing bonding during seasoning is the evaporation of water from the edges of the sheet. In work to be described later, it was found that very wet sheets (60 per cent moisture) would dry out appreciably during the 20-hour seasoning period.

The adhesive itself does not produce the change on seasoning, because after 10 minutes' seasoning, the adhesive had a strength considerably higher than that which exists between plies. If the adhesive had penetrated to the boundary, approximately the same force would have existed there as at the surface of the block.

That the "bridging over" of the glue from one block to the other can take place is illustrated by the data in Table IX. In this case the glue has apparently penetrated all the way through the thin porous sheets, made from the less beaten stock, with the result that the effect is very much as through the sheet were not there at all, while the sheets made from the more beaten stocks are apparently dense enough to prevent the penetration of the glue. The data represent the perpendicular bonding tests, obtained on 40-pound sheets (24 x 36--500) made from bleached sulfite beaten to different freenesses. Since it is well known that unbeaten stock forms sheets that have a low fiber-to-fiber bonding strength, it is obvious that the results obtained with the silicate are the correct ones and that the silicate has not penetrated even the most porous sheets, while the results obtained with glue as the adhesive are correct only at the lower freenesses, where the glue has not penetrated through the sheet.

TABLE IX

EFFECT OF ADHESIVE ON BONDING TESTS FOR THIN SINGLE SHEETS

	Adhesive	
Freeness	Glue	Silicate
850	200+	7.7
775	166+	45.4
550	79.4	81.3
415	68.5	77.6
360	68.2	85.7
285	61.6	87.4
190	68.4	90.0

In addition to the variation in the amount of moisture present in the two-ply handsheets at the time of testing, the amount of pressing given the heavy and light handsheets was not identical, even though the procedure was the same. The thicker sheet has a greater cushioning effect during pressing, causing a wider area of contact during the pressing of the thicker sheet than existed during the pressing of the thinner sheet. This means that the actual amount of pressing given the thick sheet was less than that given the thin sheet for the same force per linear inch on the roll. Increased pressure increases the bonding between plies; therefore, if pressure were the only factor, the bond in the thin sheet should be greater than that in the thick sheet, but this was not the case.

Furthermore, the ease with which the water is removed from the sheet on pressing and drying determines the magnitude of the bonding force; the more difficult the displacement of the water, the more its removal disturbs the bonding between plies. In the present case, it was easier to remove the water from the thinner sheet; therefore, this sheet should have higher bonding forces.

The final point to be considered is that, all conditions being equal, two sheets of the same material should stick together with the same force whether the sheets are thick or thin. The data contained in Table VIII indicate this to be the most probable condition, for the bonding obtained with silicate was approximately the same for both the thin and the thick sheet. The same was true when Dennison wax was used as the adhesive.

However, the values obtained with these two adhesives were not the same. The difference is reasonable on the basis of the moisture content of the sheet at the time of testing, a slight amount of excess moisture still being present in the silicate-cemented sheet after seasoning.

It is difficult to explain why such a high result was obtained with glue as the adhesive for the thick sheets after seasoning; this is especially true since the glue does not bridge over the sheet, for under that condition, the light sheet would have the higher bonding force. Furthermore, the same weight of a very porous sheet is sufficiently great so that glue does not mask the sheet, nor do the individual results indicate that the high value is possibly in error.

Due to the larger edge area, it is possible for the thicker sheet to have a lower amount of moisture present, and especially a lower percentage moisture content, after seasoning, because the same amount of water is introduced into the two sheets. This would be in line with the higher value obtained for the heavier sheet as compared with that obtained for the thinner sheet.

The perpendicular bonding tests using glue as the adhesive parallel the tests obtained for the tear split when the stiffness of the different sheets is nearly the same, as shown by Table IV and Figure 4. However, if the stiffness or thickness of two sheets differs greatly, it is not possible to compare the tearing-type bonding tests with the perpendicular bonding tests for these sheets, because the forces required to bend the two sheets in the splitting operation are too widely different. This is illustrated by the above data. The tear split value for the heavy sheet was almost twice that of the light sheet, whereas it is reasonable to believe that the actual bonding forces were the same. Stiffness tests run on the two sheets showed that the Riehle stiffness of the heavy sheet was almost seven times that of the light sheet, and the flexural stiffness was more than twenty times as great.

The effect of the moisture in the glue and silicate cements was also apparent in the tests carried out on the machine-made sheet (see Table VIII). The wax gave a slightly higher test than the silicate, and the silicate a little higher than the glue. The differences due to the different adhesives were not as great in the case of the machine sheet, primarily because the porous sheet and the larger amount of edge area allowed the same amount of water to be assimilated by the sheet and then more rapidly evaporated from the edge. Silicate is quite suitable as an adhesive for typical machine-made board, especially since the bonding forces are usually not as high as in handsheets made from relatively well beaten stock.

Summarizing, the use of glue as the adhesive in the perpendicular bonding test is less satisfactory than the use of silicate, due to the fact that the glue may penetrate the sheet. A hard nonpenetrating wax is more suitable than silicate, because it does not introduce any water into the sheet, but it is difficult to apply the wax in such a way as to give a uniform bonding over the surface of the test sample. Under normal conditions, the use of silicate is recommended, but, as the results given in Tables IV and VII show, glue can be used to give results that are approximately the same under the same conditions and different under different conditions.

Strength of Multi-ply Sheets vs. Strength of Plies

In order to determine whether the bond between plies in a multi-ply sheet plays any part in the strength tests carried out on the sheet, the relation between the strength of multi-ply board and the strength of the individual plies that go to make up that board was determined. Multi-ply sheets of unbleached sulfite pulp, with approximately the same weight but made from different number of plies, were made and tested for strength. Single plies, the same weight as the plies in the multi-ply sheets, were made and tested as units. In the case of the seven-ply sheet, seven of the single sheets were tested together as a unit, i.e., they were handled as a multi-ply sheet that had no bonding between plies.

The multi-ply sheets were couched at 3.3 pounds per linear inch and pressed at 66.7 pounds per inch. The single sheets were pressed with the same pressure. The unbleached sulfite stock had a freeness of 620. The basis weight of the multi-ply sheets was about 100 pounds. Table X shows the results obtained for the multi-ply sheets and the plies while Figure 5 presents graphically the results obtained for the individual plies.

TABLE X

STRENGTH OF MULTI-PLY SHEETS AS RELATED TO STRENGTH OF PLIES IN THE SHEET

No. of Plies	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Tear Split	Perpendicular Bonding
1	217	9.8	50.6	153.5	59.6	5.9	----	55.6
2	290	9.9	58.8	147.1	73.1	6.9	26.9	66.7
S	256	7.9	53.3	55.1	77.5	3.5	----	68.3
3	321	9.9	56.0	146.0	84.5	7.3	57.0	33.8
S	270	7.2	47.6	24.4	93.9	2.9	----	70.7
4	330	10.3	54.0	145.0	85.7	6.9	46.1	42.0
S	316	6.3	40.8	----	96.8	3.3	----	62.7
5	328	10.3	60.4	141.3	82.6	7.3	44.8	40.4
S	290	6.0	37.7	25.2	101.9	2.9	----	68.1
6	337	10.3	56.6	142.7	83.6	7.4	37.8	23.8
S	280	5.3	34.5	12.7	87.0	2.7	----	61.0
7	326	10.6	57.5	147.6	82.3	6.6	35.7	31.6
S	275	5.3	31.6	10.9	77.2	2.3	----	58.4
7xS	292	5.3	34.0	10.8	85.0	4.2	00.0	00.0
9	328	10.5	56.4	137.9	83.9	6.7	22.2	36.1
S	270	5.5	24.1	8.8	95.0	2.4	----	70.1

S = single sheet with the same weight as individual plies in the multi-ply sheet preceding
7xS = seven single sheets tested as a unit

It is obvious that an appreciable part of the strength of a multi-ply sheet comes from the bonding between plies. This is probably the result of the greater stiffness which

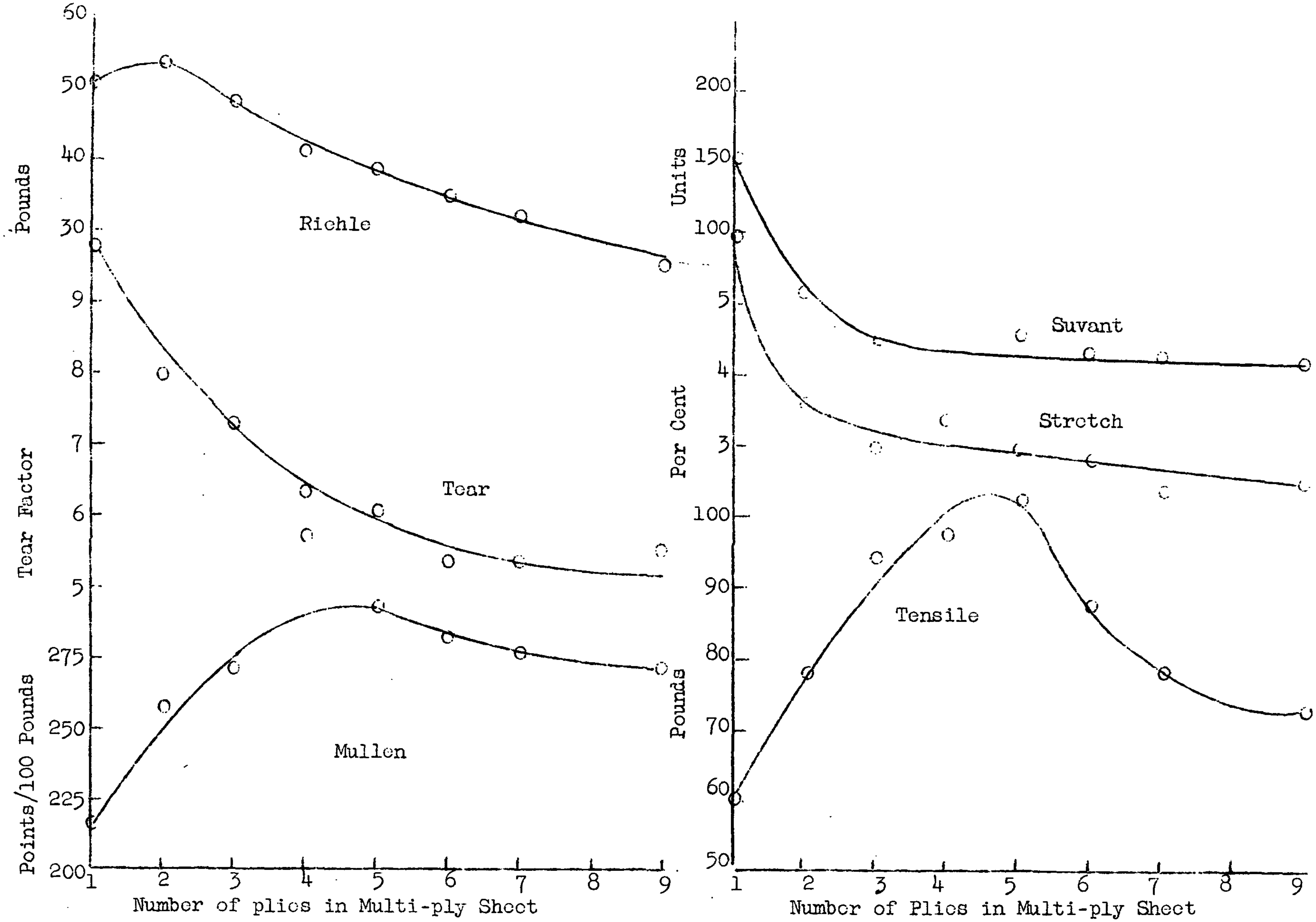


FIGURE 5. STRENGTH OF INDIVIDUAL PLIES

exists for plies bonded together than for the plies treated as units. The values reported for all the sheets are converted to a unit weight basis in order to be comparable to each other. The effect of the weight itself does not cause the increased strength in the multi-ply sheet, otherwise when seven single sheets were tested as a unit, the results obtained would be the same as those obtained with the seven-ply sheet.

The Riehle stiffness per unit weight of the single plies is a function of the weight of the ply; the lower the weight, the lower the stiffness per unit weight, but multi-ply sheets made up of these plies and bonded together have a Riehle stiffness per unit weight which is not dependent to any great extent on the weight of the plies. It is apparent, then, that the crushing of the sheet due to the application of a force against the edge of the sheet is largely dependent on how well a given weight of fiber is held together, on whether the fiber is present in the form of a multi-ply sheet or a group of unbonded sheets. The use of seven single plies as a unit shows that mere quantity of fiber is not sufficient to give a resistance to crushing that is comparable to that obtained when the plies are bonded together.

The flexural stiffness per unit weight, as determined by the Suvant tester, is also a function of the bonding that exists in a multi-ply sheet. As a strip of seven single sheets is bent, each sheet can act as an individual and is free to take the shape which offers the least resistance to the bending action. The result is that a low force is required to bend the seven-sheet unit through a given angle. In contrast to this, when the seven-ply sheet is bent, the plies are no longer free to act as individuals but are held tightly to each other, so that, instead of the stress causing one sheet to slide over the other in the bending, a tension is set up between the plies as well as inside them. The alteration in the shape of the strip on bending must result from a change in the shape of the fibers and a stretching of these fibers at the interface between plies, unless the angle of the bend is sufficiently large so that the shearing force set up at this interface exceeds the force holding the plies together, in which case the plies will split apart. This splitting takes place when boxboard is creased and folded in the manufacture of cartons.

The bursting strength per unit weight is not greatly different for the plies and the multi-ply sheet; nevertheless, in all cases the resistance to bursting of the same weight of fiber, in the form of sheets, is greater if the sheets are bonded together than if they are separate units. The bursting strength per unit weight of a single sheet is also a function of the sheet weight; a medium-weight sheet gives a higher Mullen than either a very light or a very heavy sheet. Heavier sheets have poorer formation, whereas lighter sheets have too little thickness to offer the maximum resistance to the bursting thrust that is possible for a larger amount of the fiber in question.

The Mullen test is a function of both the tensile strength and the tensile stretch of the sheet (3,4). In this experiment, the tensile strength per unit weight is slightly greater for the plies than it is for the multi-ply sheet made from these plies, but the stretch of the single plies is much less, so that the Mullen strength per unit weight is lower for the single plies than for the over-all multi-ply sheet. The greater stiffness per unit weight possessed by the multi-ply sheet also helps to produce a bursting strength per unit weight that is greater than that possessed by the single plies, because a greater force is required to shape the sheet so that it conforms to the contour of the expanding diaphram.

The tearing strength, as measured on the Elmendorf tear tester, was higher for the multi-ply sheets than it was for the plies. It is believed that the reason for this is not primarily due to a difference in the true tearing strengths of the sheets but rather to the instrument itself. It was observed that when the light sheets were torn, they tore in a line-type tear, but that during the tearing of the heavier sheets, the tear becomes an area-type tear, that is, a split. The area-type tear, of course, gave the higher value.

Summarizing, the strength of multi-ply board is greater than the combined strength of the individual plies. The bursting strength per unit weight, the flexural stiffness per unit weight, the resistance to crushing per unit weight, and the tensile stretch depend on whether or not the same weight of sheets is bonded together. Therefore, in a multi-ply sheet these strengths are a function of the bonding between plies.

Relation Between the Weight and Bonding of a Single Sheet

The fiber-to-fiber bonding in a single sheet may be different throughout the cross-section of a sheet if, in the process of drying the sheet in contact with the hot metal drier, the surface layer of fibers is dried differently from those in the center portion of the sheet, or if the removal of water from the center of the sheet reduces the bonding between fibers. The perpendicular bonding data presented in Table XI tend to show that neither of these conditions exist.

Although these data do not represent a direct study of the nature of the bonding throughout the sheet, that is, whether the surface is more tightly bonded than the interior of the sheet, it is believed that they do show the same thing. The thinnest sheet may be thought of as being analogous to two surfaces in comparison with the thickest sheet, so that the surface bonding is measured by measuring the thinnest sheet.

The results obtained vary somewhat, but there appears to be only one point of marked difference, namely, the heaviest sheet shows a slightly lower bonding strength than the other sheets. This is probably due to the difference in the way the tests were carried out; the bonding of the thickest sheet was determined with glue as the adhesive, whereas the other values were obtained using silicate as the adhesive.

TABLE XI

EFFECT OF SHEET THICKNESS ON BONDING BETWEEN FIBERS

Basis Weight	Caliper	Apparent Density	Perpendicular Bonding
92.5	24.7	3.74	55.6
43.0	11.7	3.68	68.3
30.0	8.3	3.62	70.7
23.3	6.9	3.38	62.7
17.2	5.9	2.92	68.1
16.0	5.3	3.02	61.0
13.6	4.8	2.84	58.4
9.9	4.2	2.36	70.1

The sheets used for this study are the single sheets whose preparation was described on pages 55 and 56.

There is no marked change in the bonding as the weight of the sheet is changed, but it might be said that the data show a slightly decreasing tendency as the sheet gets thinner, if it is considered that the last value in the above table is in error. It is possible that such a condition exists because, although the sheets were pressed the same way, the apparent density of the sheets became less as the sheets became thinner. This was brought about by drying the sheets in contact with the wire upon which they are formed. It is believed that this drying procedure is not a good one, because it does not allow the shrinkage of the sheets to take place, but it is difficult to place the light sheets on the drier if they are removed from the wire.

All things considered, it may be said that the bonding between fibers in a single sheet is not a function of the position in the sheet but is the same throughout the sheet, because thick sheets are bonded as well as thin sheets.

Effect of the Number of Plies on the Strength and Bonding of a Sheet of Multi-ply Board

A study was carried out in which the over-all sheet weight was kept constant, but the number of plies used to obtain this weight was varied. Several different stocks were used in the study. They have been described in part on pages 14 to 16. The sheets were couched and pressed in two different ways. The solid sheets for which the data are given in Tables XII, XIII, and XIV were pressed three times with a force of 33.3 pounds per linear inch on the roll; the three-, five-, and seven-ply sheets were couched with a force of 23.3 pounds per inch and pressed once with a force of 33.3 pounds per inch. For the unbleached sulfite sheets represented by the data in Table XV, the procedure was to couch all sheets except the one-ply sheet (which was pressed only) with a force of 3.3 pounds per inch and to press all sheets once with a force of 66.7 pounds per inch. Since it is the final pressure that governs the density of the sheet, it was possible by this procedure to obtain sheets of the same weight and with almost the same caliper but with a different number of plies.

Table XII shows the effect of the number of plies on the bursting strength of handmade board made from the stocks designated. Table XIII gives the tearing strength and Table XIV gives the Riehle stiffness of these same stocks. Table XV is for unbleached sulfite with a freeness of 620; it is part of the data presented in Table X.

TABLE XII

EFFECT OF THE NUMBER OF PLIES ON MULLEN STRENGTH

Stock	Freeness	Number of Plies 1	3	5	7
Unbleached Sulfite	630	210	232	248	238
Unbleached Sulfite	250	224	296	326	381
Bleached Sulfite	680	172	213	216	224
News-10% Sulfite	450	110	125	132	127
Chip	430	136	154	156	154
Kraft-sulfite	530	152	182	178	172
Unbleached Kraft	810	266	272	272	304
Groundwood-sulfite	520	138	162	161	161

TABLE XIII

EFFECT OF THE NUMBER OF PLIES ON TEARING STRENGTH

Stock	Freeness	Number of Plies 1	3	5	7
Unbleached Sulfite	630	7.7	9.1	8.0	7.1
Unbleached Sulfite	250	7.8	7.6	8.3	7.6
Bleached Sulfite	680	7.1	6.9	8.1	6.7
News-10% Sulfite	450	5.2	4.6	3.8	4.8
Chip	430	6.2	6.2	5.8	6.8
Kraft-sulfite	530	6.9	7.0	6.9	7.3
Unbleached Kraft	810	12.8	12.1	11.7	10.9
Groundwood-sulfite	520	4.5	5.3	5.9	5.7

TABLE XIV

EFFECT OF THE NUMBER OF PLIES ON RIEHLE STIFFNESS

Stock	Freeness	Number of Plies 1	3	5	7
Unbleached Sulfite	630	54.7	46.4	53.0	47.5
Unbleached Sulfite	250	65.5	68.8	69.9	75.4
Bleached Sulfite	680	45.3	45.2	45.1	40.9
News-10% Sulfite	450	50.1	53.1	53.1	45.0
Chip	430	47.3	44.2	36.5	37.5
Kraft-sulfite	530	43.5	42.3	42.2	40.2
Unbleached Kraft	810	46.4	39.6	44.3	44.9
Groundwood-sulfite	520	48.0	47.0	46.4	39.6

TABLE XV

EFFECT OF THE NUMBER OF PLIES IN SHEETS OF UNBLEACHED SULFITE

No. of Plies	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Tear Split	Perpendicular Bonding
1	3.74	217	9.9	50.6	153.5	59.6	5.9	----	55.6
2	3.89	290	9.9	58.8	147.1	73.1	6.9	26.9	66.7
3	3.94	321	9.9	56.0	146.0	84.5	7.3	57.0	33.8
4	4.00	330	10.3	54.0	145.0	85.7	6.9	46.1	42.0
5	3.98	328	10.3	60.4	141.3	82.6	7.3	44.8	40.4
6	3.99	337	10.3	56.6	142.7	83.6	7.4	37.8	23.8
7	4.01	326	10.6	57.5	147.6	82.3	6.6	35.9	31.6
9	4.11	328	10.6	56.4	137.9	83.9	6.7	22.2"	36.1

" Ply tore before split was completed

As the number of plies used to make up the same weight of multi-ply sheets is increased, the strength of the board is increased up to a certain point, but the use of too large a number of plies results in decreased strength as measured by the Mullen test. The tensile strength of the multi-ply sheets increases up to a certain point and then becomes constant as the number of plies is increased. The Riehle stiffness stays almost constant, but the flexural stiffness decreases a little as the number of plies is increased.

Several stocks were used to determine the effect of the number of plies on the Mullen strength; for almost all these stocks there is a point between three and five plies where the Mullen reaches a maximum. (Figure 6) The location of this maximum will vary with the over-all weight of the multi-ply board and the nature of the stock being used.

Since all the sheets used in this study were made in a sheet mold, using the same amount of water for each ply, the quality of the formation which the plies will possess for any one stock is dependent on the consistency used in forming the sheet. The same condition exists on the cylinder machine as in the sheet mold. There it is common practice to carry as much water as the system will allow, so that if any additional stock is introduced, the formation will not be as good as before.

Therefore, the solid, or one-ply sheets, will have the poorest formation if the weight of the board desired is at all typical of boxboard. When the same weight of sheet is made from two plies, the formation will be much better, since the consistency from which the plies are formed will be only half as much as before. As the number of plies is increased, a ply-weight will soon be reached beyond which any decrease in weight will produce but little improvement in formation.

This means that if the formation were the only factor that governed the Mullen test in this case, it might be expected that this value would increase rapidly at first, but the rate of increase would then begin to be smaller and at a certain number of plies the Mullen test would become almost constant. However, each time another ply is used in making up a sheet of multi-ply board, another point of potential weakness is introduced at the boundary between the plies. Whether such a weakness will actually result from the use of another ply will depend on the nature of the stock and the number of plies already present, but the primary consideration is whether the removal of the water from the sheet during pressing and drying becomes more difficult, so that a reduction in the bonding force between one or more pairs of plies will result.

As shown before (Table X), the Mullen strength obtained for a given weight of plies is higher when those plies are bonded together. Therefore, if there is a weakness due to poor bonding in a multi-ply sheet, the Mullen obtained on that sheet will be less than that obtained if the plies were all tightly bound.

In the case of the unbleached sulfite sheets represented in Table XV and by Figure 7, the weight of the sheet and the nature of the stock were such that the maximum Mullen was reached when about five plies were used. Upon looking at the graphic representation of the data for the strength of the individual plies (Figure 5), it will be seen that also in this case the Mullen reached a maximum at about five. This maximum was brought about, in part, by the effect of a different factor, namely, the sheet shrinkage, since there is no bonding between plies to contribute a weakness to the sheet. However, a somewhat similar weakness is introduced, and that is a decreased bonding between fibers, caused by a decrease in the amount of shrinkage of the sheets, and thus in the apparent density of the sheets.

The Mullen increased first due to better formation, but as the weight of the individual plies became less and the sheet so thin and bulky, the maximum resistance to bursting that could have been offered, if the amount of fiber present had been allowed to shrink completely, was not obtained. On the other hand, the density of the multi-ply sheets increased slightly as the number of plies was increased, due to better formation and a little more pressing. The quality of formation is the more important cause of this increase. This means that if the sheet density of the multi-ply sheets could have been held constant, the Mullen for the multi-ply sheets would have gone through an even sharper maximum.

Considering the data of Table XII (represented by Figure 6), the two stocks that are the exceptions to the maximum-in-Mullen condition help to substantiate the postulation that better formation causes the Mullen to increase as the number of plies is increased. The unbleached kraft stock was very free (freeness 810) so that, even when seven plies were used to make up the multi-ply sheet, the increasing quality of the formation was still the controlling factor. In fact it was necessary to increase the number of plies to five before there was an appreciable improvement in formation, as indicated by the Mullen curve. The other extreme of beating is represented by the unbleached sulfite with a freeness of 250.

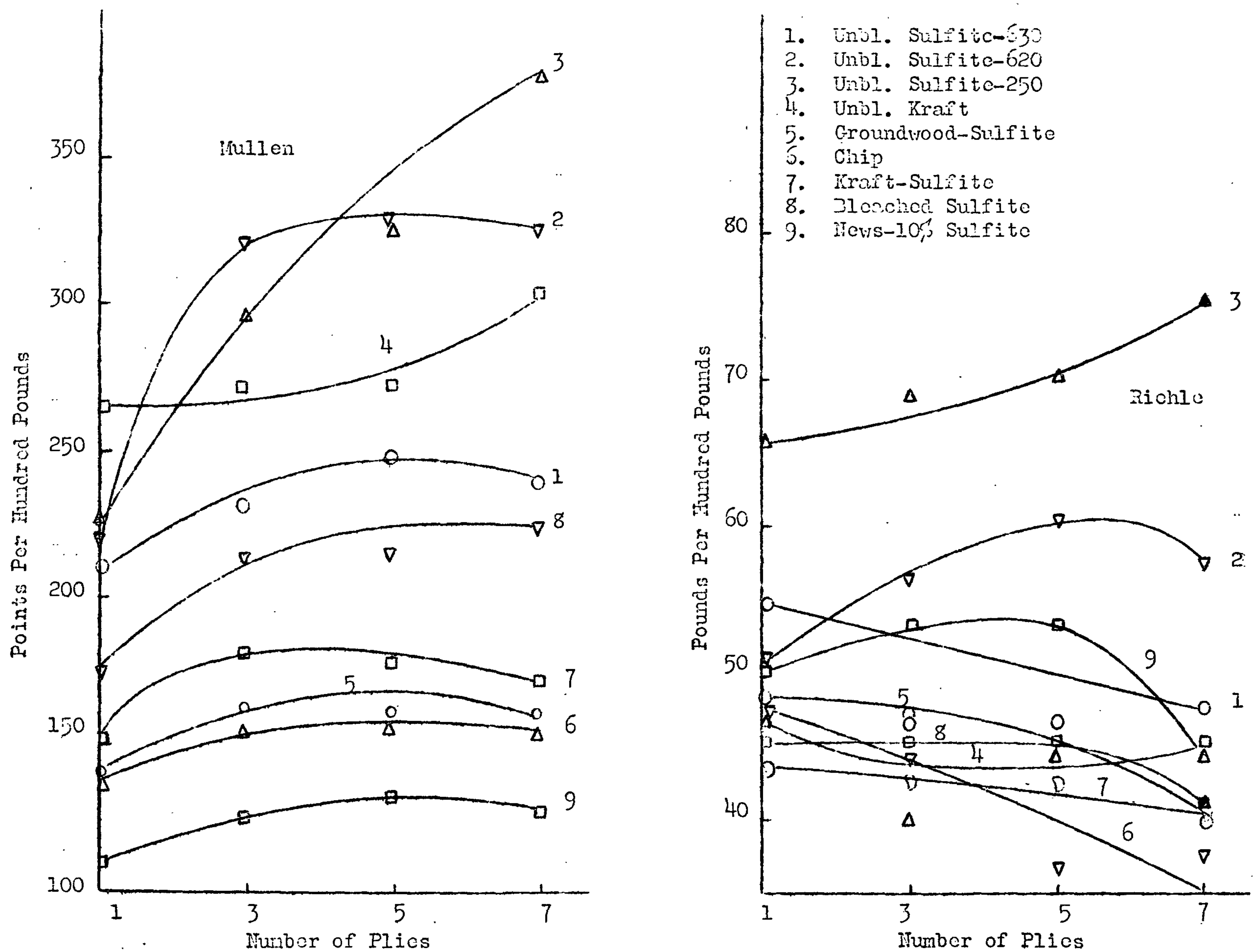


FIGURE 6. EFFECT OF THE NUMBER OF PLIES ON STRENGTH

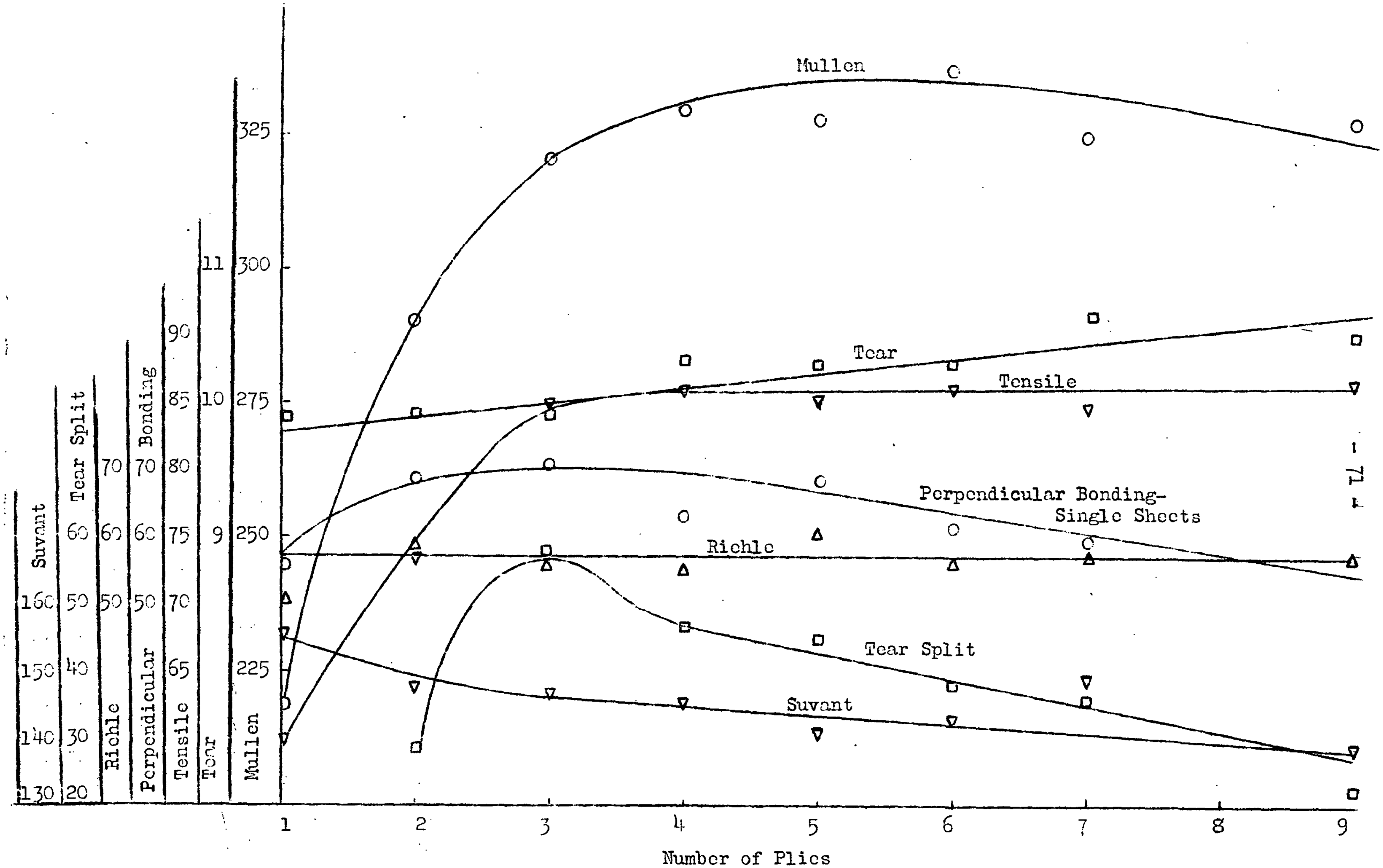


FIGURE 7. EFFECT OF THE NUMBER OF PLIES ON STRENGTH OF UNBLEACHED SULFITE

This stock was just as hard to form as the very free stock, especially since less water was used in its formation. The introduction of weakness at the ply interfaces may not have happened in this case, for unless water removal ruptures portions of the interface, the bond at the interface was stronger for this stock than the plies themselves. This will be shown later.

The tensile strength of the unbleached sulfite (Fig. 7) increased to maximum at a number of plies that was one less than that at which the Mullen reached a maximum and then remained practically constant. Table XV shows that the stretch remained practically constant for any number of plies. This means that, for the Mullen to decrease while the tensile and stretch remain constant, some other factor such as weakness between plies must enter into the test. The weakness between plies will not show up in the tensile strength, because this test does not require any bonding between plies to give the maximum value for a unit weight of fiber (Table X). The flattening of the curve for the tensile strength of the multi-ply sheets can be directly related to the decrease in the rate of improvement of formation. The maximum present in the tensile strength curve for the single plies can best be attributed to an increase in quality of formation combined with a decrease in the density of the sheet which results in a lower tensile strength.

The bonding results obtained by both the perpendicular bonding and the tear split tests need some explanation and clarification. The results presented in Table XV for the perpendicular bonding show the force required to split the sheet at the weakest point in the sheet. In all cases, this place was at one of the boundaries between plies. The data serve to illustrate the introduction of weakness into the sheet as the number of plies is increased. In the two-ply sheet where water removal need not disturb the bond between plies, the bonding force was high, being very nearly that which existed between the fibers in the individual plies. As more plies were used, the water removal caused a disturbance of the bond between plies so that the bonding at the weakest ply interface was not nearly as great as that between the fibers in the plies, although it may have been at other interfaces in the sheet.

Instead of measuring the weakest point in the sheet, the tear split test was carried out to measure the bonding between the top and second plies in each case. This ply interface should not be affected greatly by the removal of the water from the sheet. Why such a low force is required for the splitting of the two-ply sheet cannot be explained, especially since the perpendicular bonding for that interface is so high. If it is assumed that the top two plies are bonded together with the same force for any number of plies in the sheet, the decreasing force required to split them by the tear split test in going from the three- to the nine-ply sheet can be explained on the basis of the decreasing resistance of the top ply to bending, for when this ply is heavy and stiff, most of the force needed is required to bend this ply during the splitting. As the stiffness of the ply becomes less (Table X and Figure 4), the force required to split the sheet becomes less and more nearly that required to split the bond itself.

The resistance to tearing possessed by the multi-ply sheets was usually not affected by the number of plies used to make the sheet. The tear values obtained on the Elmendorf tester showed a tendency to increase as the number of plies increased. This may be attributed to increased splitting during the tear when there were present more surfaces that could be split apart as they were torn across. The reverse of this was evident in the case of the unbleached kraft where the formation was increasing so much with the increasing number of plies that the sheet tore more in a line and the tearing force became less as the number of plies was increased. However, on the whole, the tearing strength of a multi-ply sheet is relatively independent of the number of plies.

The Riehle stiffness is not appreciably affected by increasing the number of plies. Well hydrated sheets show the most change, usually a slightly increasing resistance to the crushing action in the test. For the case of the unbleached sulfite represented in Table XV and Figure 7, increasing the number of plies caused a slight decrease in the flexural stiffness of the sheets, but not nearly the decrease shown by the individual plies. It would appear that improved formation does not appreciably affect the stiffness of the sheets, and the bonding between plies affects it only slightly if the sheets do not split.

It may be said that the number of plies that are used to make a multi-ply sheet affects the strength of the board. However, multi-ply paperboard possesses one fundamental difference from laminated materials. In the case of the latter, the lamination is carried out by cementing together sheets which possess approximately the same strength per unit weight, irrespective of the thickness. At the same time, the adhesive used is different from the sheets themselves. In the case of multi-ply board, conditions of forming the plies that make up the board are such that the nature of the ply changes as the thickness changes, due to changes in the quality of formation in the plies. At the same time, the material which causes the cementing of the plies in a multi-ply board is a part of the ply itself. Therefore, it is possible to have a point of maximum strength for some given quality of stock and weight of sheet. Such a condition would also exist for sheets made on a commercial cylinder machine, as well as for sheets made in a sheet mold.

Bonding Between Plies as a Function of Position in Sheet

A study has been made of the bonding forces between different plies in a multi-ply sheet. The bonding between each pair of plies in a seven-ply sheet of unbleached sulfite was measured by the tear split test and the weakest point in the same sheet was measured and located by the perpendicular bonding test. These tests were repeated for another seven-ply sheet of unbleached sulfite, for a seven-ply news-20% sulfite sheet, and a seven-ply sheet, the top two plies of which were unbleached sulfite and the bottom five plies news-20% sulfite.

The work was continued using three-ply sheets of unbleached sulfite, two plies of which were constant and the third one varied with respect to the amount of beating. All three plies, for any set of stocks, were varied with respect to position in the sheet, i.e., with respect to each other and the top and bottom. All sheets were couched at 3.3 and pressed at 66.7 pounds per inch.

In Table XVI:

A = 7-ply sheets (99.3 pounds per 1000 sq. ft.) of unbleached sulfite; freeness 620; splitting area, 1 x 3 in.

B = 7-ply sheet (98.0 pounds per 1000 sq. ft.) of unbleached sulfite; freeness 530; splitting area, 1 x 2 1/2 in.

C = 7-ply sheets (100.7 pounds per 1000 sq. ft.) of news-20% unbleached sulfite; freeness 310; splitting area, 1 x 2 1/2 in.

D = 7-ply sheets (100.1 pounds per 1000 sq. ft.), top two plies of unbleached sulfite, freeness 530; bottom five plies of news-20% unbleached sulfite, freeness 310, all plies having the same weight; splitting area, 1 x 2 1/2 in.

TABLE XVI

BONDING BETWEEN THE DIFFERENT PLIES IN A SEVEN-PLY SHEET

	Tear Split Between Plies						Perpendicular Bond.	
	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	Force	Position
A	33.1	36.6	28.0	23.9	46.9	33.7	----	----
B	38.0	48.9	34.7	28.2	43.8	38.1	73.1	2 - 3
C	T	T	18.7	18.2	T	T	35.9	2 - 3
D	35.0	42.6	19.0	13.4	36.6	T	48.4	3 - 4

T = Plies split instead of bond

From these data it is apparent that, when all the plies are the same, the bonding force between plies is dependent on position, with respect to top or bottom, of the interface in question.

If all the plies in a sheet are made from the same stock, the weakest interface, as measured by the tear split test, is always at the same place, no matter what the nature of the stock. When the weakest point is determined by the perpendicular bonding test, the same is true, but this test locates the weakest point at an interface different from that indicated by the tear split test.

When part of the plies are made from one stock and the remainder from another, the tear split test indicates that the weakest point is at the interface in the same position as in the previous case. However, the perpendicular bonding test locates the weakest point at an interface different from that in the previous cases and different from that indicated by the tear split test on the same sheets.

For all the cases studied, the tear split test indicated the weakest bond to be between the fourth and fifth plies from the top. On the other hand, when the plies were all the same, the perpendicular bonding test located the weakest point at the interface between the second and third plies. When this interface was a heterogeneous boundary, namely, news--sulfite, the weakest point indicated by the perpendicular bonding test was between the third and fourth plies.

It is difficult to decide which test locates the weakest point correctly, unless the different types of splitting measure different types of forces holding the plies together. It does not seem likely that the moisture introduced into the test sample, using glue as the adhesive, in the perpendicular bonding test would concentrate at any one interface in a homogeneous sheet and thus cause that interface to become the weakest point in the sheet. Since this is the only factor recognized as influencing the perpendicular bonding test, it must be believed that the weakest interface indicated by this test must actually be the weakest one with respect to a force normal to the surface.

The stiffness of the portion of the sheet being split off in the tearing type test influences the values obtained for the test. As the test was carried out, the force required to bend the plies during the splitting would increase in going from the 1 - 2 to 2 - 3 to 3 - 4 positions and in going from the 6 - 7 to 5 - 6 to 4 - 5 positions. An inspection of the data for the "B" sheets in Table XVI shows that although the bending force required is greater for the 3 - 4 position than it is for the 2 - 3 position, the bonding value obtained is less even though the perpendicular test showed the 2- 3 position to be the weaker.

The conclusion to be drawn from these considerations is that the two tests measure splitting forces sufficiently different in nature so that the tests do not indicate the same position in a multi-ply sheet as the weakest one. However, the close parallelism in other cases indicates that both these forces change in the same manner with changing conditions of sheet preparation.

Table XVII shows the results obtained on the three-ply sheets when the freeness of one of the plies was varied as well as the position of the plies with respect to each other and the top and bottom of the sheet.

TABLE XVII

BONDING BETWEEN PLIES AS A FUNCTION OF POSITION AND FREENESS

Freeness of Plies			Tear Split		Perpendicular Bond.	
Top	Middle	Back	Top - Middle	Middle - Back	Force	Position
775	380	830	27.8	19.1	28.5	M - B
775	830	380	17.9	10.1	12.1	M - B
830	775	380	17.3	12.4	21.3	T-M-B
830	380	775	18.2	23.4	21.5	T - M
380	830	775	10.8	11.3	11.7	M - B
380	775	830	21.3	11.0	24.5	M - B
775	380	690	32.8	32.5	36.5	T - M
775	690	380	29.5	21.0	38.4	T - M
690	775	380	26.7	15.1	34.8	M - B
690	380	775	38.9	25.2	43.7	M - B
380	690	775	32.4	13.4	47.3	B
380	775	690	23.1	17.8	28.6	M - B
775	380	550	34.2	22.2	46.5	T - M
775	550	380	31.3	22.8	40.4	T - M
550	775	380	25.5	18.9	32.6	M - B
550	380	775	47.7	27.3	52.0	M-B B
380	550	775	X	31.5	44.0	B
380	775	550	20.0	16.1	29.8	M - B
775	380	415	36.3	30.6	38.5	T - M
775	415	380	31.6	34.9	33.4	T - M
415	775	380	20.2	16.9	34.6	M - B
415	380	775	X	32.0	48.3	B
380	415	775	X	33.7	48.1	B
380	775	415	19.5	17.0	37.8	M - B
775	380	245	34.5	X	42.6	T - M
775	245	380	36.8	37.9	43.5	T
245	775	380	17.6	16.6	36.2	M - B
245	380	775	X	34.8	49.0	B
380	245	775	X	36.7	48.3	B
380	775	245	20.5	18.8	38.3	M - B

X = Ply tore instead of bond
T = Top ply
M = Middle ply
B = Back ply

TABLE XVII - Continued

	Weight	Caliper	Apparent Density
First Group	56.3	14.4	3.91
Second Group	57.1	13.5	4.25
Third Group	56.2	13.3	4.25
Fourth Group	58.5	13.9	4.21
Fifth Group	57.9	13.5	4.30

These data again indicate the fact that the bonding between two plies is dependent on their position in the sheet, relative to the top and bottom. In this case the differences which exist when the interface is at the same position in the sheet, but the plies are reversed in position with respect to each other, are also shown.

Considering the interface between a ply made from the stock with a freeness of 775 and a ply made from the stock with a freeness of 380, the data for the tearing-type bonding test presented in Table XVII allow the effect of the freeness of the other ply to be determined.

(a) When the interface in question is between the top two plies and the slower stock is in the middle ply, increasing the amount of beating of the stock in the back liner causes an increase in the bonding at the interface until the freeness of the back liner stock becomes less than that in the middle ply. Then the bonding becomes somewhat less.

(b) When the interface in question is between the top two plies and the slower sheet is the top liner, increasing the amount of beating given the back liner stock causes an increase in the bonding at the interface, until the freeness of the back liner stock is less than that of the middle ply; then there is a slight decrease in the bonding.

(c) When the interface in question is between the lower two plies and the slower stock is in the bottom ply, increasing the amount of beating given the top liner stock causes an increase in the bonding at the interface until the stock is relatively well beaten; then there is a slight decrease.

(d) When the interface in question is between the bottom two plies and the slower stock is in the middle ply, increasing the amount of beating of the top liner stock causes a fairly large and steady increase in the bonding at the interface.

(e) When the interface in question is between the top two liners, the bonding at the interface is considerably greater if the less completely beaten stock is on the outside of the sheet.

(f) When the interface in question is between the bottom two plies, the bonding between plies is twice as great when the slower stock is in the middle ply instead of in the back liner.

(g) When the interface in question is between either the top two or the bottom two plies, with the slower stock in the middle ply, the bonding is greater if the interface is between the top and middle plies.

(h) When the interface in question is between either the top two or the bottom two plies, and the freer stock in the middle ply, the bonding is greater when the interface is between the top and middle plies.

Considering the interface between the ply made from stock with a freeness of 775 and the ply made from stock at various freenesses, the data in Table XVII show the following:

(a) When the interface in question is between the top two plies and the freer stock is in the top liner, the bonding at the interface increases as the amount of beating of the one ply is increased. The increase is most rapid for the first part of the beating.

(b) When the interface in question is between the top two plies and the freer stock forms the middle ply, the bonding at the interface increases for the first part of the beating of the one ply, passes through a maximum and then returns almost to the original value.

(c) When the interface in question is between the bottom two plies and the freer stock forms the middle ply, the bonding at the interface increases at the very beginning of the beating of the one ply but then remains practically constant at a relatively low value.

(d) When the interface in question is between the bottom two plies and the freer stock is in the bottom ply, the bonding at the interface increases rapidly at first as the one stock is beaten and then continues to increase more slowly.

(e) When the interface in question is between the top two plies, the bonding at the interface is greater if the slower stock forms the middle ply instead of the top ply, the extent of the difference increases as the difference between the freenesses of the two stocks at the interface increases, being small for a slight difference but being as much as 100 per cent for the largest difference.

(f) When the interface in question is between the bottom two plies, the bonding at the interface is greater if the slower stock forms the middle ply instead of the back ply.

(g) When the interface in question is between either the top two or the bottom two plies and the slower stock is in the middle ply, the bonding at the interface, with the variable ply at any given freeness, not below 600, is greater if the interface is between the top two plies instead of the bottom two. Below a freeness of 600, the bonding at the interface is nearly the same whether the boundary is between either the top or bottom two plies.

(h) When the interface in question is between the top two or the bottom two plies, and the freer stock is in the middle ply, the bonding between the plies for the variable ply at any given freeness is greater if the interface is between the top and middle plies. The difference is less at either end of the beating range than it is at the middle.

Considering the interface between the ply made with stock at a freeness of 380 and the ply made with stock at various freenesses, the data in Table XVII indicate the following:

(a) When the interface in question is between the top two plies and the freer stock forms the top liner, the bonding at the interface increases rapidly until the one ply has a freeness of about 500; then the strength of the bonding between plies is greater than the strength of the freer ply so that the ply splits rather than the bond.

(b) When the interface in question is between the top two plies and the slower stock forms the top liner, the bonding between plies increases rapidly until the one ply has a freeness of about 500; then the bonding between plies is greater than the strength of the freer ply.

(c) When the interface in question is between the bottom two plies and the freer stock forms the back liner, the bonding between plies increases rapidly at first and then remains practically constant as the amount of beating of the one ply is increased.

(d) When the interface in question is between the top two plies, the bonding at the interface is higher when the freer stock is in the top liner. However, the freer stock tends to split under these conditions rather than the bond.

(e) When the interface in question is between the bottom two plies and the slower stock is in the back liner, the bonding at the interface increases slowly as the freeness of the one stock decreases to about 400. Then the freer sheet splits, since the bond is stronger than the ply.

(f) When the interface in question is between the bottom two plies, the bonding at the interface is greater if the slower stock is in the middle ply. The difference is less, the more nearly the two plies become the same.

(g) When the interface in question is between either the top two or the bottom two plies and the slower stock is in the middle ply, the bonding at the interface is greater if it is located between the top and middle plies.

(h) When the interface in question is between either the top two or the bottom two plies with the freer stock in the middle liner, the bonding between plies is greater if the interface is between the top and middle plies. The bond becomes sufficiently strong after the one ply is beaten a small amount so that the freer ply splits rather than the bond.

Summarizing the data in a general manner, it may be said that the bonding between two plies that are the same is dependent on the nature of the rest of the sheet and their position in the sheet. Increasing the amount of beating of a third ply causes the bonding force to change, the amount and nature of the change being dependent on the relative freeness of the different stocks and the position of the plies.

For any given stock, or stocks, the bonding between two plies is dependent on their position relative to each other and with respect to top and bottom of the sheet. The bonding is greater when the interface is between the top and middle plies of a three-ply sheet than when it is between the middle and back plies. The bonding is much greater if the freer sheet is on the outside of the interface.

As the amount of beating of one ply in a three-ply sheet is increased, and the other two plies kept constant, the bonding between plies increases until either the fibers in the freer sheet are bonded together with a force that is less than that of the bond at the ply interface, or until the sheet has been beaten to such an extent that the removal of water across the interface is difficult and the bonding between plies is disturbed by its removal.

For any given freeness, better bonding is obtained when the freer ply is on the outside of the sheet. When the variable ply is made with stock of a moderate degree of beating, and the slower stock forms the middle ply, the bonding is greater if the interface is between the top and middle plies. However, for the interface between a ply of well beaten stock and a ply of relatively unbeaten stock, the position is not important because the bonding inside the freer sheet is the controlling factor. When the slower stock is on the outside of the sheet, the upper position permits a higher bonding force to exist.

Many of the changes which take place at the interface are a result of the differences in the amount and rate of water removal during drying and especially during pressing. The ease with which the water contained in the plies can be removed across the interface determined the final bonding. The physical mechanism of this action is easily understood.

However, there are conditions under which it is not easy to see from a physical picture how water removal alone can change the bonding force in the manner observed. Therefore, at least one other factor must help control the bond ing under these conditions, and the two effects oppose each other.

Starting with Campbell's statement (7,8) that greater bonding between fibers on beating results only because of the increased surface area per unit weight, a mechanism which is general for the bonding between plies may be postulated.

The action which causes the bonding between plies to vary is not a change in the fiber itself but a change in the amount of actual contact area between plies. Any action that will decrease the actual area of contact will decrease the bonding between plies; any action that will increase the amount of contact will increase the bonding between plies.

In this instance, the removal of water across the interface causes a reduction in the number of contacts and therefore in the bonding between plies, whereas the action which causes increased bonding to take place is dependent on the amount of water present at the interface at the time of pressing the sheet.

The more water present in the sheet, i. e., the greater the moisture content of the plies being pressed together, the greater will be the freedom of motion of the fibers on the surfaces at the interface. The effect may be compared to the effect of using more water in the forming of a sheet; the formation will be better, the surface of the sheet will be smoother and more compact, and the fibers in the sheet will tend to contact each other more completely. The result of these effects would be a tighter sheet. Such a condition may be thought of as existing at the interface during the pressing.

The initial couching pressure used is not sufficient to cause many contacts between the fibers of the opposite surfaces. This is shown later in the work on the effect of pressing on bonding. It is the final pressing of the multi-ply sheet that causes the real bonding between plies to take place. The drying of the fibers that are put into contact by pressing completes the cementing of fibers and plies together. However, too rapid a drying action may cause this bonding action to be reduced because pockets of steam may not be able to escape from the sheet.

As the sheets go through the press rolls, the fibers on the surfaces of the plies may be said to flow. The more water there is present, the more the fibers of one ply will move to fill up the surface of the other ply. This produces a more nearly continuous structure. The higher the pressure that is used, the more the fibers will be pressed against each other to form a more intimate contact, with the result that the bonding force is greater for the larger area of contact.

To illustrate the two mechanisms which control the bonding between plies, consider the results pointed out in (a) for the case of the interface between the plies with freenesses of 775 and 380. The nature of the stocks at this interface is always the same, but the freeness of the stock used for the back liner is decreasing. This means that after the couching operation there is a greater amount of water present at the interface during the pressing operation when the back liner stock is slower. This is brought about by the greater water-holding capacity of the well beaten stock for the same conditions of pressing, which results in an increase in bonding. However, at the same time, the disrupting force of the water being removed across the interface is active. When the combination of the bottom and middle plies is such that it is very difficult for the water to get out through them in the pressing operation, most of it will go across the top interface. Under this condition, the reduction of the contact area by the water passage is greater than the increase in the amount of contact permitted by the greater amount of water, and the bonding at the interface decreases as the freeness decreases.

In the work on the three-ply sheets, the perpendicular bonding tests agree a little more closely with the tear split test than was the case for the seven-ply sheets. In most cases, the two tests indicated the same point of weakness in the sheet, whether it was between plies or within a single ply. The disagreement that exists is primarily due to the perpendicular bonding test splitting the freest ply just at the interface rather than the interface itself. Each stock was tinted with dye to facilitate the location of the position of the split.

A question might be raised as to whether the tear split test did not also split the ply and not the interface if the perpendicular test found the ply to be the weaker point in the sheet. This was not the case. It is apparent again that the two tests do not measure exactly the same kind of bonding. All tearing-type splits were clean unless otherwise noted.

In the tear split test carried out on the interface between the two constant stocks, the stiffness of the ply being removed was always the same for either the case of the freer stock or the slower stock on the outside. Stiffness, therefore, was not a factor in the test. However, at the interfaces where the stock of decreasing freeness was to be split off, the stiffness of the ply was a variable. This means that the tear split will increase a little as the stock is beaten, due to an increase in the stiffness of the ply. In this work, such an increase was not sufficient to overshadow the change in bonding produced by beating.

The positions at which the plies of different freeness were placed greatly affected the amount of curl which the sheets possessed, both when they came from the drier and after they had been seasoned. The curl was always toward the ply that had been made from the slower stock, and when this stock was greatly different from the others, the sheet would curl until it was in the form of a cylinder. If the slowest ply was in the center of the sheet, the sheet remained flat.

It is usually believed that the curling of commercial board is influenced chiefly by the moisture content of the different plies. This may well be the case if it is considered that the amount of "hydration" given a stock by beating helps to control the hygroscopic nature of the stocks in the final multi-ply sheet. It may also be that the tendency to curl is caused by the differences in the amount of shrinkage which the different stocks undergo when the sheet is dried. The tendency to curl could be reduced if the amount of shrinkage of each stock was adjusted so that it was the same as the others. The differences in the shrinkage and the differences in the rate of water absorption and equilibrium moisture content of the different stocks are related to the same thing, the so-called "hydration" of the stock.

Effect of Couching Pressure on Strength Properties and the Bonding Between Plies

For this study, several different stocks were used. They included unbleached sulfite, unbleached kraft and news-10% unbleached sulfite. The unbleached sulfite was used at different freenesses. The character of the stocks will be designated a little more completely at the place where the results obtained for that stock are presented.

Table XVIII presents the variations in the strength properties of a six-ply sheet, with a basis weight of about 110 pounds, all plies equal, made from unbleached sulfite pulp with a freeness of 510, as the couching pressure is changed. All sheets were given a final pressing with a force of 150 pounds per inch acting on the sheet. Table XIX shows the changes in the bonding in two-ply sheets, with a basis weight of about 60 pounds, made as above from the same stock. The plies in this case were relatively heavy. The use of heavy plies was intended to eliminate the effect of the adhesive in the perpendicular bonding test, and later, when strength tests were run on two-ply sheets, to give strength values in the range of light weight boards. The Mullen strength and the bonding tests are compared graphically in Figure 8.

TABLE XVIII

EFFECT OF COUCHING PRESSURE ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 510

Couching Pressure	% Dry, Couched	Appar. Density	Mullen	Tear	Suvant	Riehle
10.0	30.6	4.38	319	12.1	217	67.5
13.3	30.4	4.42	319	12.1	209	72.2
33.3	31.9	4.45	345	10.5	222	72.6
50.0	35.3	4.54	375	9.8	206	70.2
64.7	27.4	4.62	401	9.9	236	73.8
82.3	39.4	4.68	391	10.4	242	73.8
150.0	42.5	4.92	413	9.6	207	71.3

TABLE XIX

EFFECT OF COUCHING PRESSURE ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 510

Couching Pressure	% Dry, Couched	Perpendicular Bond.	Forman Tester		
			Initial	Maximum	Average
10.0	25.1	74.5	360	400	410
13.3	25.6	83.4	410	440	435
23.3	29.6	72.8	380	380	380
33.3	31.1	77.8	330	400	375
50.0	36.4	79.6	380	380	380
64.7	38.2	77.3	360	440	390
82.3	39.5	60.7	260	330	285
100.0	40.6	71.8	350	370	360
116.7	41.6	66.7	320	320	320
150.0	44.2	71.0	360	390	340

Table XX presents the strength properties of six-ply board, with a basis weight of about 120 pounds, made from

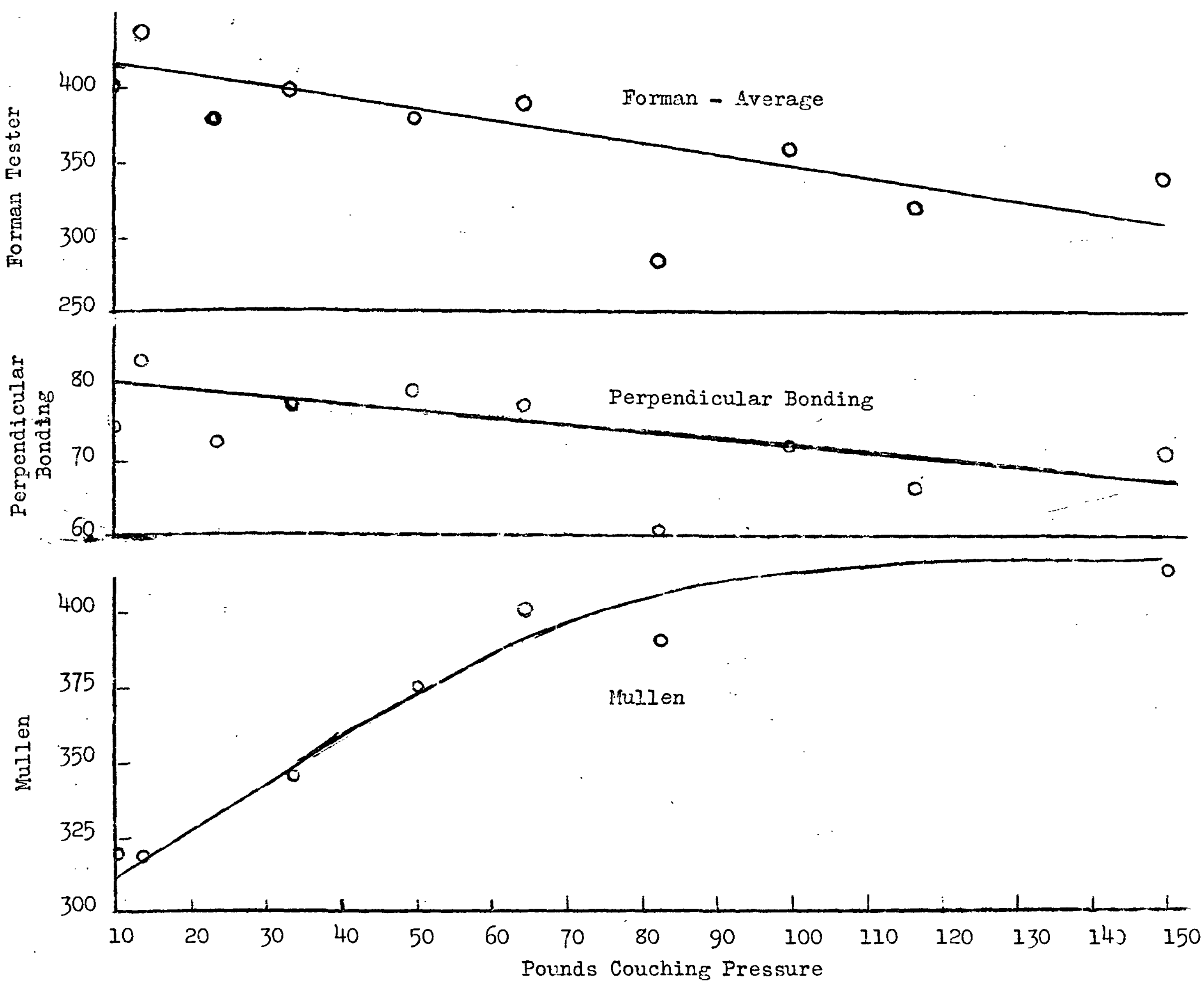


FIGURE 8. EFFECT OF COUCHING PRESSURE ON UNBLEACHED SULFITE--FREENESS 510

unbleached sulfite at a freeness of 735, couched with different pressures and finally pressed with a force of 150 pounds per linear inch. Table XXI contains the bonding results obtained both for the six-ply sheets and two-ply sheets, with a basis weight of about 65 pounds, made from the same stock and by using the same final pressure. Figure 9 graphically represents the Mullen and Riehle stiffness results for the six-ply sheets as well as the perpendicular bonding tests for the two-ply sheets.

TABLE XX

EFFECT OF COUCHING PRESSURE ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 735

Couching Pressure	% Dry, Couched	Appar. Density	Mullen	Tear	Suvant	Riehle
13.3	34.2	4.50	305	12.2	223	54.0
23.3	36.7	4.33	301	11.4	197	58.8
33.3	37.9	4.43	328	11.3	231	59.9
50.0	40.6	4.53	327	12.7	228	60.2
82.3	45.5	4.65	338	12.2	221	63.6
116.7	46.8	4.72	350	11.0	244	66.9
150.0	48.2	4.82	350	14.2	236	69.6

TABLE XXI

EFFECT OF COUCHING PRESSURE ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 735

		Two-ply Sheets				Six-ply Sheets			
Couch. Press.	%Dry, Couch.	Perpendicular Bonding	Forman Tester Init.	Forman Tester Max.	Forman Tester Av.	Perpendicular Bonding	Forman Tester Init.	Forman Tester Max.	Forman Tester Av.
13.3	26.8	----	296	327	323	33.0	429	800	635
23.3	28.2	47.3	227	273	246	52.5	448	800	599
33.3	37.8	47.5	268	268	268	39.7	495	920	701
50.0	40.6	51.3	296	395	365	56.5	509	825	667
82.3	45.0	47.0	264	304	292	48.3	300	543	349
116.7	46.8	49.1	331	331	331	46.3	486	907	708
150.0	49.5	55.0	300	300	300	49.3	618	1048	834

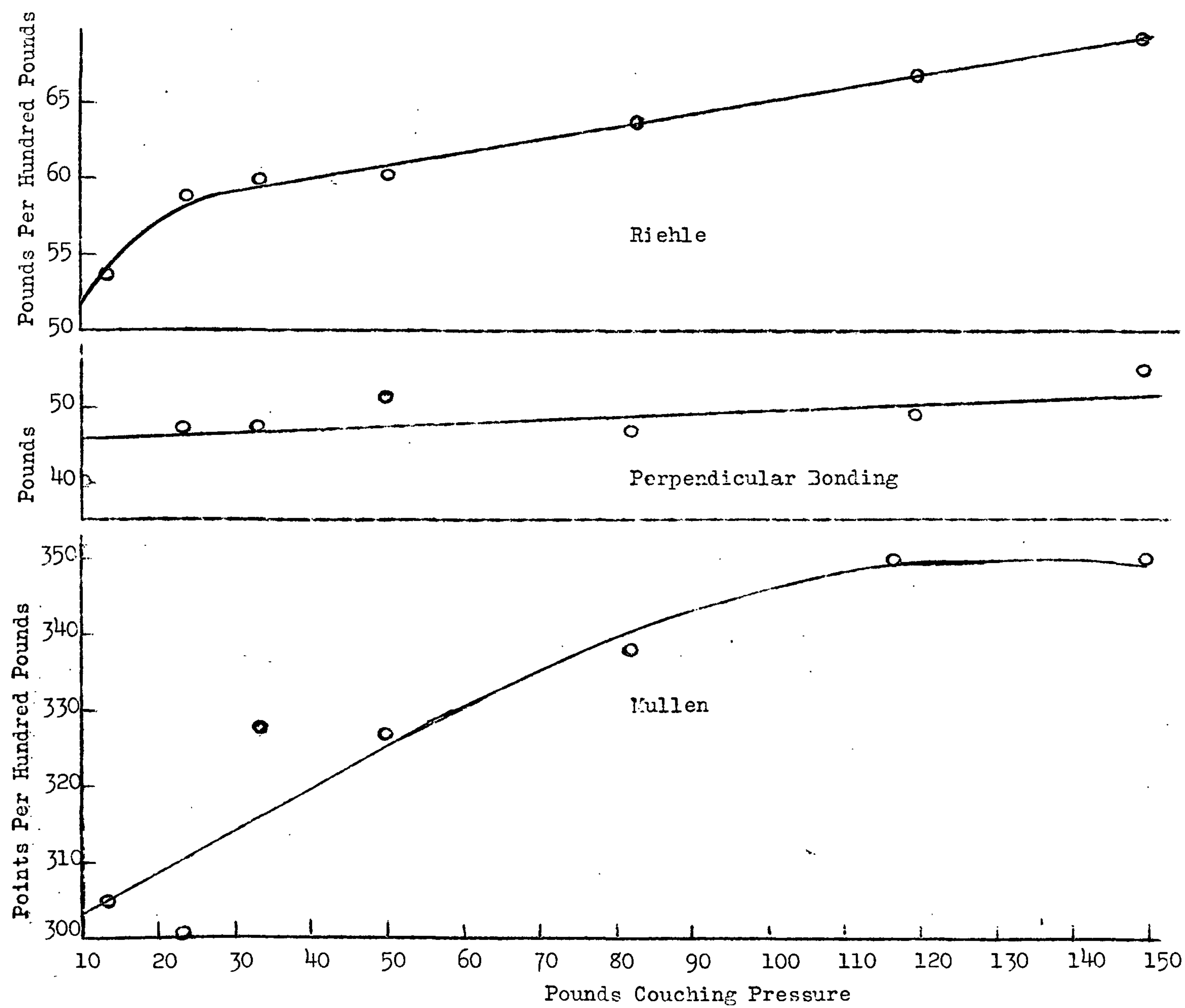


FIGURE 9. EFFECT OF COUCHING PRESSURE ON UNBLEACHED SULFITE--FREENESS 735

Table XXII gives the results obtained by varying the couching pressure used to make six-ply sheets, with a basis weight of about 110 pounds, from unbleached kraft pulp with a freeness of 770. Table XXIII shows the bonding between plies for two-ply sheets, with basis weights of about 60 pounds, made from this stock. All sheets were pressed with a force of 150 pounds per inch. Figure 10 represents the bonding and Mullen results in the form of graphs.

TABLE XXII

EFFECT OF COUCHING PRESSURE ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED KRAFT--FREENESS 770

Couching Pressure	% Dry, Couched	Appar. Density	Mullen	Tear	Riehle	Suvant	Tensile
10.0	35.4	4.55	387	9.6	72.0	201	91.1
13.3	33.9	4.41	391	10.9	79.4	206	91.9
23.3	36.4	4.53	424	10.5	79.4	218	91.1
33.3	37.0	4.55	429	10.3	80.0	204	93.0
50.0	42.0	4.59	438	10.3	75.4	201	99.3
64.7	43.2	4.65	428	10.2	82.0	211	96.5
82.3	45.8	4.75	451	10.5	79.6	208	93.2
100.0	47.2	4.78	442	10.4	84.6	194	92.5
116.7	49.1	4.82	433	10.4	87.1	195	93.2
133.3	47.6	4.80	449	10.1	89.8	193	96.0
150.0	49.7	4.86	454	9.7	80.9	210	93.7

TABLE XXIII

EFFECT OF COUCHING PRESSURE ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF UNBLEACHED KRAFT--FREENESS 770

Couching Pressure	% Dry, Couched	Perpendicular Bond.	Tear Split
10.0	23.9	97.8	22.6
13.3	23.6	94.7	23.4
23.3	30.0	88.2	22.3
33.3	36.9	98.4	21.7
50.0	40.5	98.8	21.5
64.7	43.3	91.1	21.5
82.3	45.9	89.7	20.1
100.0	47.1	91.1	21.5
116.7	48.8	91.4	21.5
133.3	49.1	103.3	19.0
150.0	45.6	88.7	19.4

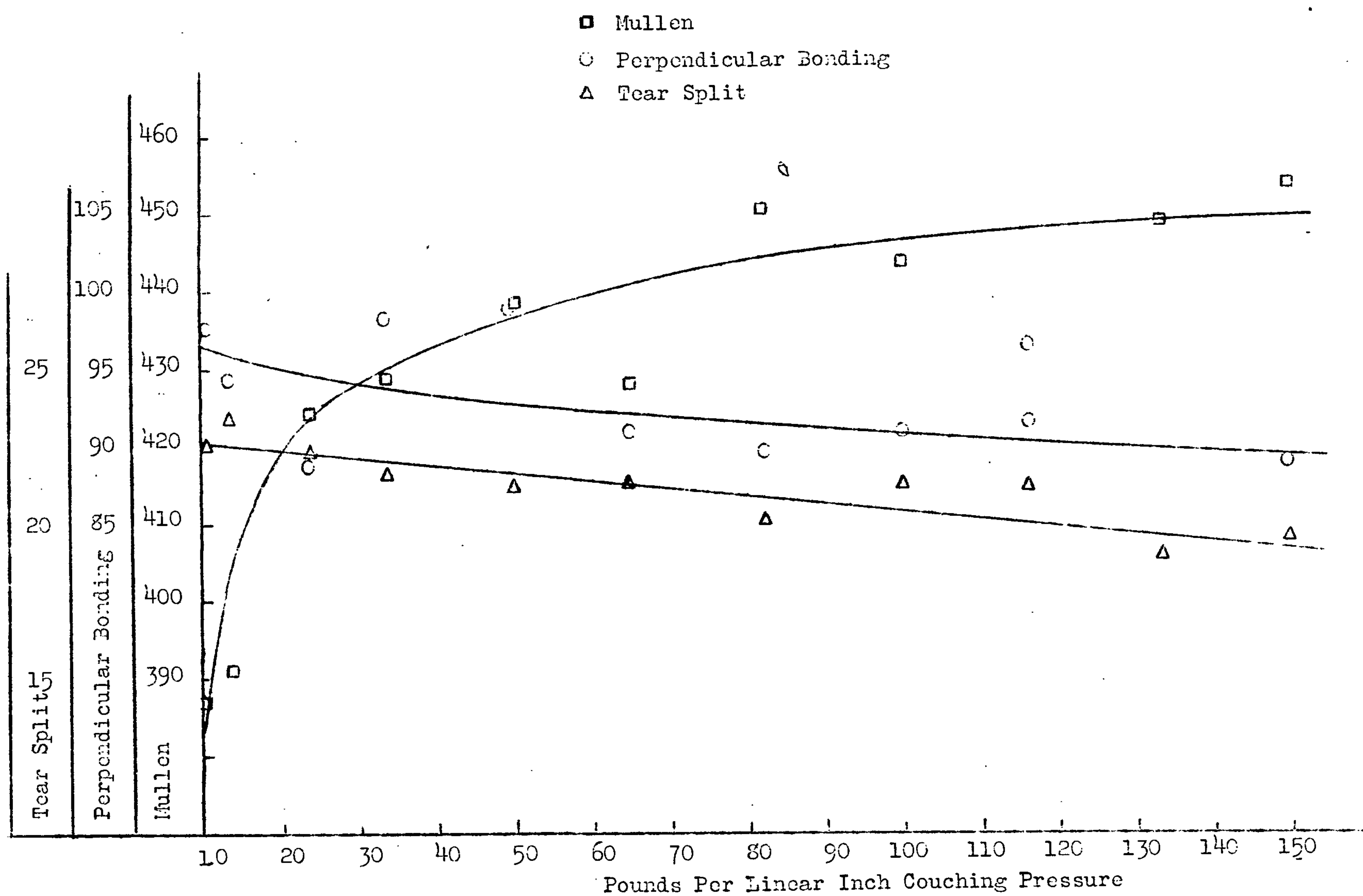


FIGURE 10. EFFECT OF COUCHING PRESSURE ON UNBLEACHED KRAFT

Table XXIV presents the data obtained with six-ply sheets, with basis weights of about 93 pounds, made from a news-10% unbleached sulfite furnish, with a freeness of 425, as the couching pressure was varied; the final pressure was constant at 150 pounds per inch. Table XXV presents the bonding results obtained for two-ply sheets, with basis weights of about 58 pounds, made from the same stock. Figure 11 contains graphic representations of the Mullen, tear and bonding results.

TABLE XXIV

EFFECT OF COUCHING PRESSURE ON STRENGTH OF SIX-PLY SHEETS OF NEWS-10% SULFITE--FREENESS 425

Couching Pressure	% Dry, Couched	Appar. Density	Mullen	Tear	Riehle	Tensile
10.0	32.8	2.93	132	----	47.4	46.1
13.3	31.3	2.96	128	3.92	49.6	42.9
23.3	34.3	2.89	135	3.94	46.6	43.7
33.3	35.9	2.97	140	4.14	47.7	45.8
50.0	41.8	2.99	149	4.10	49.8	45.8
64.7	42.9	3.04	149	3.87	47.3	45.7
82.3	46.4	3.08	151	4.02	46.5	44.9
100.0	48.7	3.11	159	4.20	48.2	46.7
116.7	48.7	3.16	157	4.30	42.6	44.9
133.3	52.1	3.17	164	4.52	49.3	42.8
150.0	52.4	3.23	164	4.78	48.2	46.2

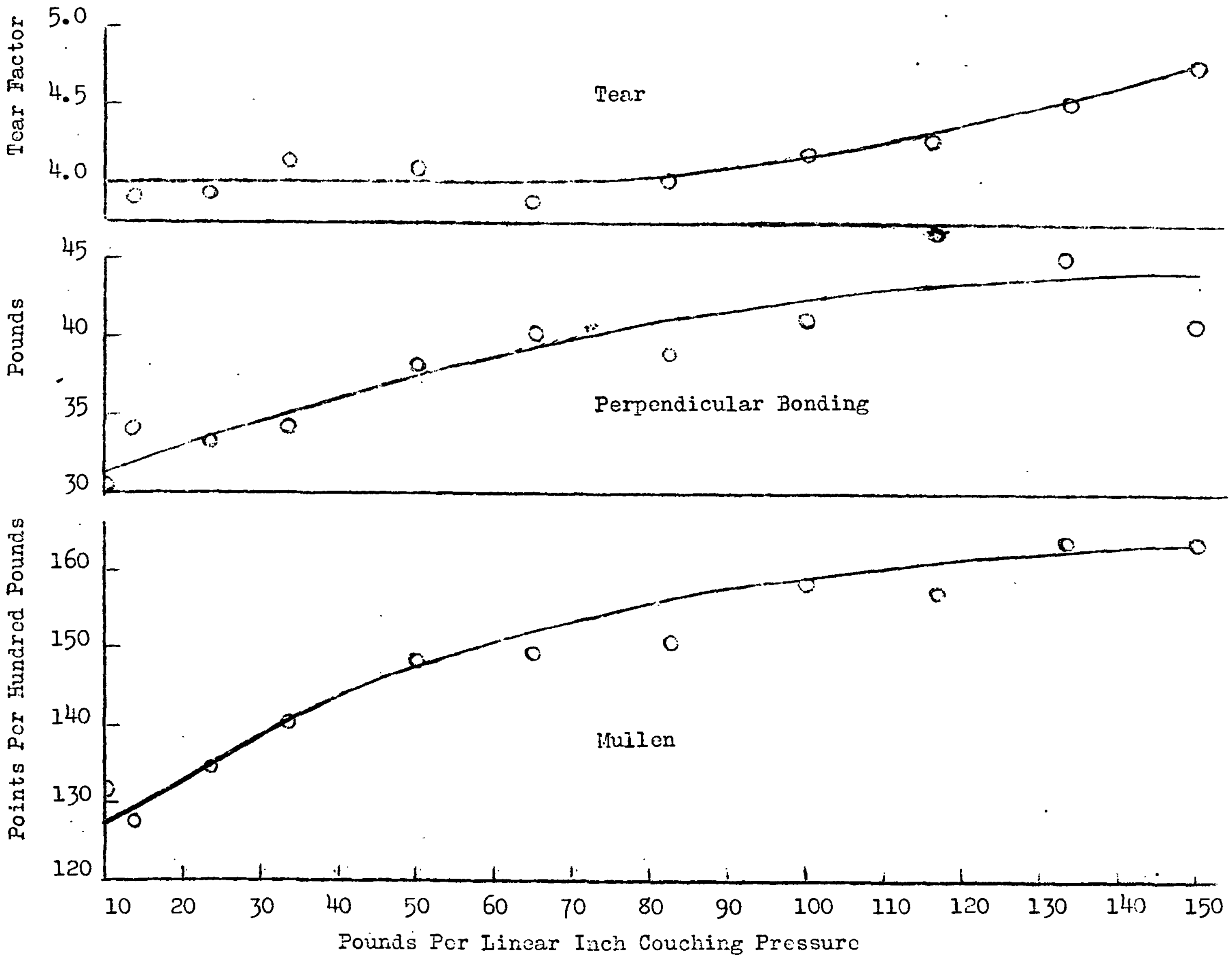


FIGURE 11. EFFECT OF COUCHING PRESSURE ON NEWS-SULFITE

TABLE XXV

EFFECT OF COUCHING PRESSURE ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF NEWS-10% SULFITE--FREENESS 425

Couching Pressure	% Dry, Couched	Perpendicular Bond.	Tear Split
10.0	28.6	30.5	10.1
13.3	25.8	34.3	9.4
23.3	29.4	33.5	9.8
33.3	36.6	34.2	10.2
50.0	37.2	38.2	10.4
64.7	41.5	40.4	13.8
82.3	45.5	38.7	10.6
100.0	46.7	41.2	10.2
116.7	48.6	47.0	13.0
133.3	50.0	45.3	11.3
150.0	50.0	41.0	11.3

In order to compare the effect of the amount of couching and pressing given the multi-ply sheets with the effect of the pressing on the plies alone, single sheets with basis weights of about 13.5 pounds and of unbleached sulfite with a freeness of 620 were made using different wet-pressing pressures. The sheets were dried in contact with the wires upon which they were formed and pressed. Under this condition, little shrinkage can take place when the sheet is dried. This is not desirable, but the sheets could not have been placed on the drier if they had been removed from the wires.

The results obtained by varying the amount of pressing given the single sheets are shown in Table XXVI and Figure 12.

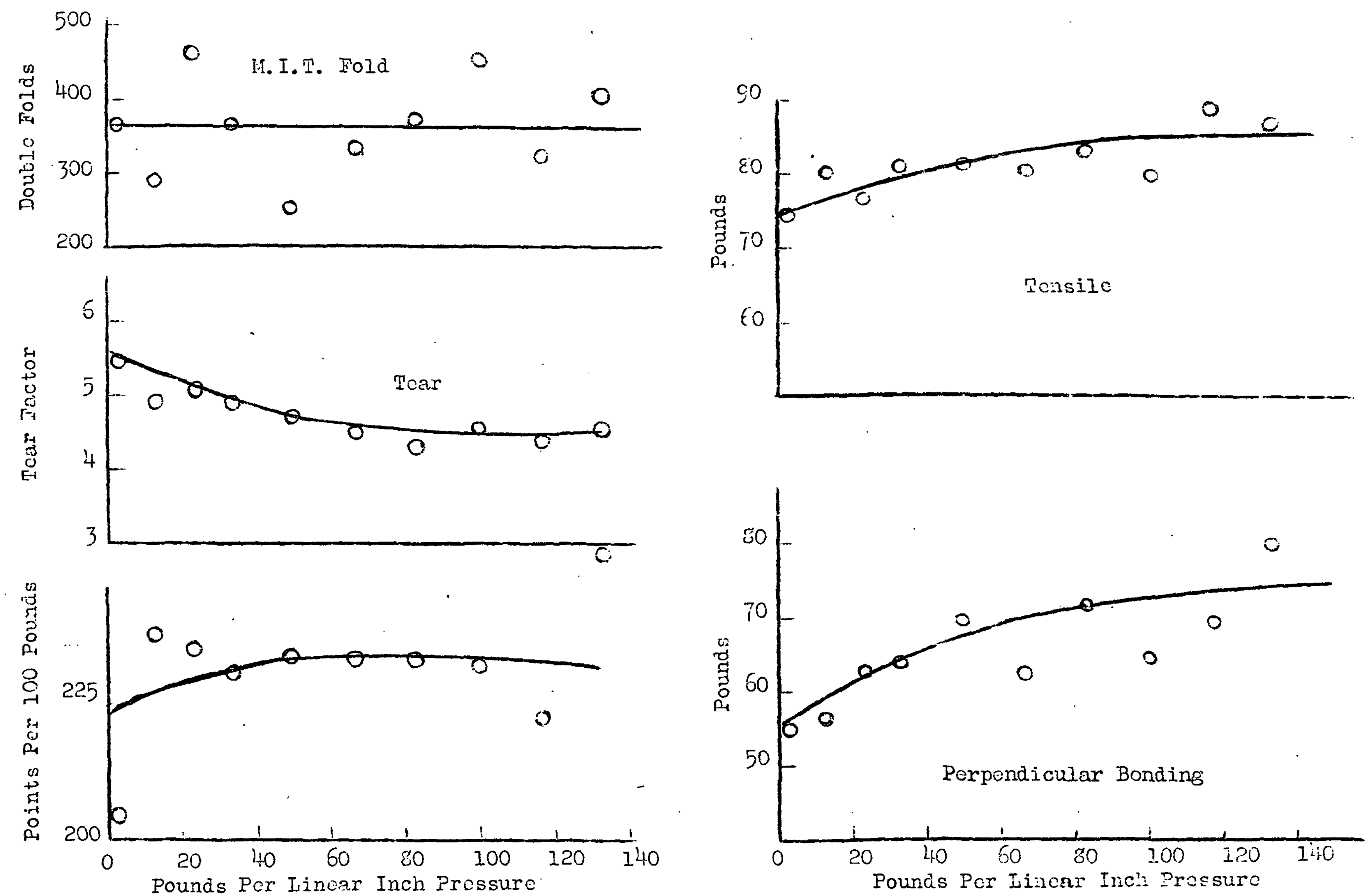


FIGURE 12. EFFECT OF PRESSING ON SINGLE SHEETS

TABLE XXVI

EFFECT OF WET-PRESSING ON PROPERTIES OF SINGLE SHEETS OF UNBLEACHED SULFITE--FREENESS 620

Pressure	Appar. Density	Mullen	Tear	Fold	Tensile	Stretch	Perpendicular Bond
3.3	2.80	207	5.41	363	74.6	2.94	54.6
13.3	2.98	234	4.96	294	80.1	3.74	56.2
23.3	2.90	232	5.06	465	77.0	3.10	62.7
33.3	2.70	228	4.90	369	81.1	3.08	63.8
50.0	2.62	231	4.70	254	81.1	3.04	69.7
66.7	2.55	230	4.45	337	80.9	3.12	62.6
83.3	2.63	230	4.33	376	83.5	3.12	71.8
100.0	2.59	229	4.56	456	80.4	3.50	64.3
116.7	2.62	220	4.39	323	89.0	3.34	69.6
133.3	2.60	250	4.56	407	87.2	3.54	73.1

For all stocks, increasing the couching pressure caused an increase in the Mullen strength of the six-ply sheets, the rate of increase becoming less at the higher pressures so that the type of curve obtained was very similar to that obtained on beating stock. This might be expected on the basis of Doughty's work (1,2) on the effect of wet-pressing on the tensile strength of the sheet.

However, in the case of multi-ply sheets, the effect of the bonding between plies is also important in determining the Mullen strength of a sheet. Increasing the couching pressure will either increase or decrease the bonding between plies, depending on the nature of the stock. In either case the change will be small.

The bonding between sheets made from well-beaten unbleached sulfite pulp decreases a little as the couching pressure is increased, whereas the bonding between plies made from slightly beaten unbleached sulfite shows a tendency to increase. The bonding for moderately hydrated kraft tends to decrease, but the news-10% sulfite there is an increase in the bonding between plies as the couching pressure increases.

Considering the nature of these stocks, it will be seen that the bonding for those that are hydrated tends to decrease, while for those that are not hydrated very much the tendency is for the bonding to increase with increasing couching pressure. (When the term "hydrated" is used, it has the meaning commonly accepted by mill men.) This is understandable on the basis of the mechanism postulated for the amount of water present at the interface at the time of pressing and the relation between the actual area of contact and the bonding force.

For unhydrated sheets, such as news, the surface of the plies at the interface is relatively rough so that an increased amount of pressing results in an increase in the amount of area of contact between the surfaces of the plies. Decreasing the amount of water present at the interface at the time of pressing will result in a smaller area of contact, but for such coarse unfibrillated stock this effect will not be as great as the effect of pressing the fibers together.

On the other hand, for well hydrated or fibrillated stocks, the surfaces at the interface are more regular, and without any final pressing the area of contact is fairly large. Increasing the total amount of pressing will increase the area of contact, but not as much as it is reduced when there is less water present at the interface during pressing, due to the use of the higher couching pressures.

Doughty and Baird (19) found that to secure good bonding it was necessary that the sheets be joined together at a much higher pressure than that at which they were couched. They used a "slightly beaten" unbleached sulfite pulp. It is possible that this might be the case with their procedure of pressing the sheets separately in the couching operation and subsequently joining them together. Well pressed plies have a relatively small amount of liquid water available; therefore, when the well pressed plies were joined together, it was necessary to use a much higher joining pressure than was used for the couching pressure in order to bring the water to the interface so that the two surfaces might "flow" together during the pressing operation. Mere pressing together evidently does not give a great enough contact area to cause a good bonding force. The condition that Doughty and Baird found need not exist when the wet fiber mats are couched together rather than separately.

For the bonding together of the fibers in a single ply, the effect of pressure is much more important than the amount of water present. During the formation of the sheet, these fibers intermesh so that it is only necessary that they be forced into contact with each other by the pressing operation in order to secure good bonding. The action brought about by the water at the interface between plies has already taken place for the fibers during the formation of the sheet.

Therefore, although the bonding between plies may decrease, increased pressure results in greater contact between the fibers in the plies, thus causing increased bonding and sheet density, so that the Mullen increases much as it would if bonding and density were increased by beating.

The reason that there was not a correspondingly large increase in the Mullen strength when the amount of wet-pressing given the thin single sheets was increased may be traced back to the density of the sheets. The density of the thin single sheets was changed little by the pressing, because these sheets were dried upon the wires upon which they were formed and could not shrink very much during drying. Therefore, since the pressing did not result in an increased sheet density, the Mullen did not increase appreciably.

The stiffness of the multi-ply sheets was apparently affected only slightly by increasing the couching pressure. With the exception of the Riehle stiffness for the sheets made from unbleached sulfite stock with a freeness of 735, the stiffness of the sheets remained practically constant for all couching pressures.

The tearing strength of the sheets made with the kraft and sulfite stocks did not vary appreciably with the couching pressure, but the tearing strength of the news sheet increased with couching pressure. The tearing strength of the thin single sheets decreased slightly as the amount of wet-pressing was increased.

Summarizing, increasing the couching pressure has little effect on any of the strength properties of a multiply sheet, except Mullen strength. The Mullen increases as the couching pressure is increased. For hydrated stocks, the bonding between plies decreases a little as the couching pressure is increased; for unhydrated stocks, the bonding increases with couching pressure.

Effect of Final Pressing on Strength Properties and the Bonding Between Plies

This study included work on two-and six-ply sheets of unbleached sulfite at various freenesses, unbleached kraft at a freeness of 770, and news-10% sulfite at a freeness of 425; in addition, a mixed two-ply sheet was studied. The top ply was unbleached sulfite at a freeness of 595; the bottom ply was news-10% unbleached sulfite at a freeness of 255.

The data given in Table IV and represented in Figure

4 show the effect of final pressing on the bonding for unbleached sulfite with a freeness of 595.

The data given in Table XXVII show the effect of the final pressure on the strength properties of six-ply sheets, with basis weights of about 117 pounds, made from unbleached sulfite stock with a freeness of 530. TableXXVIII shows the effect of final pressing on the bonding in the six- and two-ply sheets. The two-ply sheets had a basis weight of about 67 pounds and were made from the same stock as the six-ply sheets. All sheets were couched at a pressure of 10 pounds per inch. The six-ply sheets were 30.8 per cent dry after couching while the two-ply sheets were 27.3 per cent dry. Figure 13 represents the effect of various pressures on the Mullen strength and the Suvant stiffness and also includes the effect on the perpendicular bonding in the two-ply sheets.

TABLE XXVII

EFFECT OF FINAL PRESSING ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 530

Final Pressure	% Dry, Pressed	Appar. Density	Mullen	Tear	Suvant	Riehle
0.0	30.8	4.29	359	10.8	---	----
10.0	30.9	4.38	339	10.1	260	63.6
13.3	30.9	4.31	360	12.1	266	58.6
23.3	32.3	4.20	361	13.4	252	66.7
33.3	32.3	4.25	347	11.3	260	60.8
50.0	33.4	4.33	358	11.7	244	60.8
64.7	34.1	4.36	359	12.2	215	64.6
82.3	35.0	4.26	345	10.8	255	62.0
100.0	37.6	4.35	348	11.2	243	66.1
116.7	37.0	4.52	332	12.1	226	69.1
133.3	37.4	4.58	315	10.6	206	67.9
150.0	38.3	4.47	314	10.0	222	72.5

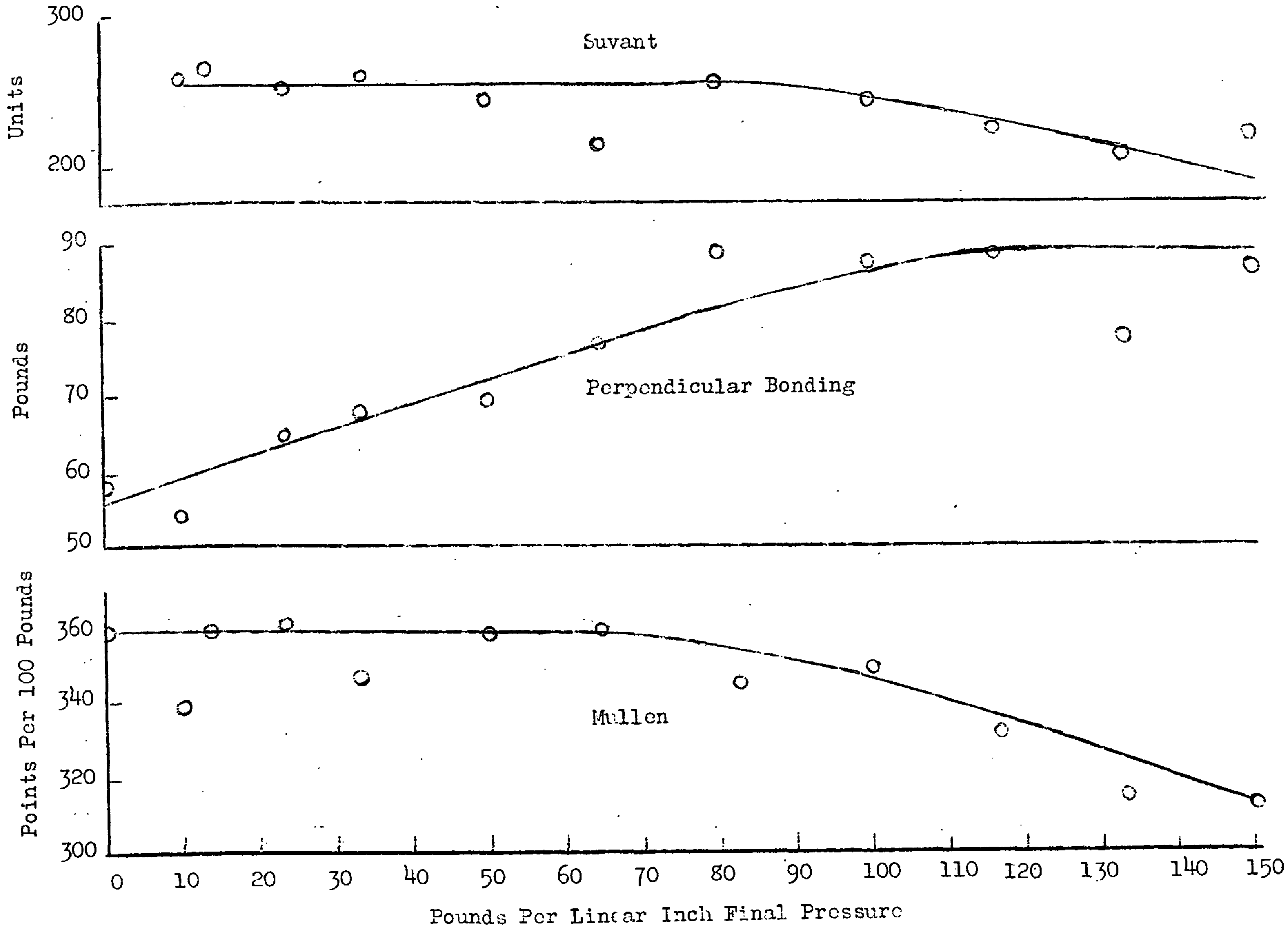


FIGURE 13. EFFECT OF FINAL PRESSURE ON UNBLEACHED SULFITE--Freeness 530

TABLE XXVIII

EFFECT OF FINAL PRESSING ON BONDING BETWEEN PLIES IN SHEETS OF UNBLEACHED SULFITE--FREENESS 530

		Two-ply Sheets				Six-ply Sheets			
			Forman Tester				Forman Tester		
Final Press.	%Dry, Press	Perpendicular Bonding	Init.	Max.	Av.	Perpendicular Bonding	Init.	Max.	Av.
0.0	27.3	58.7	495	495	495	20.9	660	1290	1026
10.0	28.9	54.4	475	510	500	25.0	640	1280	950
13.3	28.2	----	300	430	385	25.2	600	1400	992
23.3	30.0	65.3	565	565	565	29.9	600	1100	945
33.3	31.8	68.0	470	470	470	26.8	700	1410	1041
50.0	33.4	69.7	400	445	430	28.0	800	1350	1023
64.7	36.1	76.7	410	410	410	38.6	760	1270	1061
82.3	36.7	88.9	530	530	530	48.7	740	1220	1043
100.0	39.2	87.5	514	514	514	----	610	1360	978
116.7	39.6	88.7	623	738	696	----	600	1440	1051
133.3	42.2	77.7	496	610	575	----	770	1180	1022
150.0	42.7	86.4	380	420	395	----	810	1100	985

Table XXIX gives the results obtained by varying the final pressure for six-ply sheets, with basis weights of about 118 pounds, made from unbleached sulfite with a freeness of 735. Table XXX shows the effect of the final pressure on the bonding in two-ply sheets, with basis weights of about 65 pounds, made from the same stock. The six-ply sheets were 36.1 per cent dry, and the two-ply sheets 32.2 per cent dry, after couching with a force of 10 pounds per inch. The Mullen strength and the Riehle stiffness results for the six-ply sheets, and the perpendicular bonding in the two-ply sheets are represented by graphs in Figure 14.

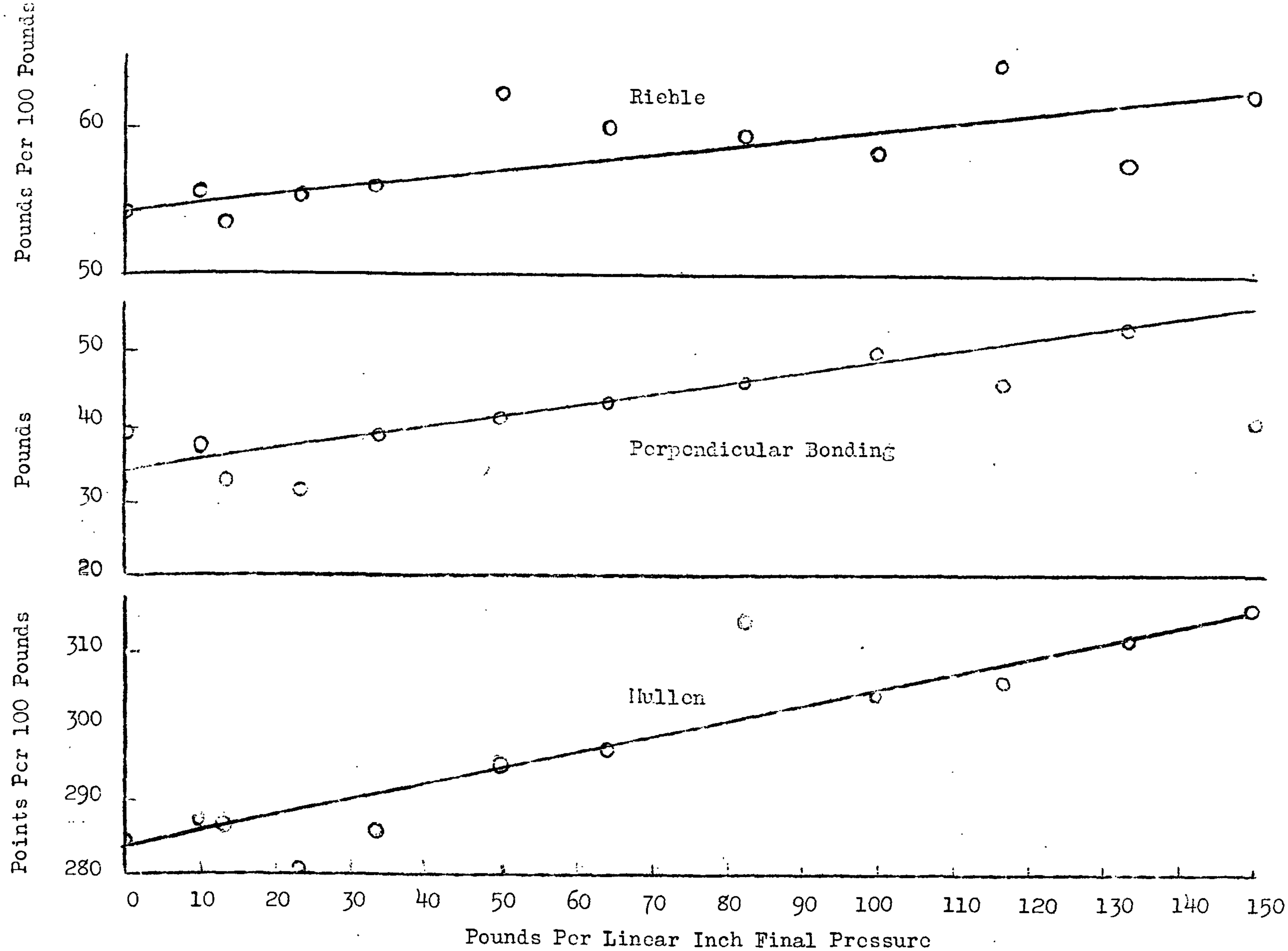


FIGURE 14. EFFECT OF FINAL PRESSURE ON UNBLEACHED SULFITE--FREENESS 735

TABLE XXIX

EFFECT OF FINAL PRESSING ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED SULFITE--FREENESS 735

Final Pressure	% Dry, Pressed	Appar. Density	Mullen	Tear	Suvant	Riehle
0.0	36.1	3.92	285	10.9	233	54.1
10.0	38.2	3.94	288	11.7	282	55.8
13.3	37.6	4.01	286	10.0	242	54.0
23.3	38.0	3.95	281	11.7	240	55.6
33.3	39.9	4.10	286	10.0	279	56.3
50.0	41.6	4.24	295	11.4	218	63.5
64.7	42.6	4.27	296	12.6	211	60.1
82.3	44.7	4.34	314	10.9	203	59.8
100.0	46.2	4.40	304	11.2	238	58.5
116.7	46.4	4.43	306	11.8	240	64.5
133.3	48.5	4.43	312	12.1	211	57.8
150.0	48.7	4.41	316	11.0	315	63.0

TABLE XXX

EFFECT OF FINAL PRESSING ON BONDING BETWEEN PLIES IN SHEETS OF UNBLEACHED SULFITE--FREENESS 735

		Two-ply Sheets				Six-ply Sheets			
Final	% Dry,	Perpen-	Forman Tester			Perpen-	Forman Tester		
Press.	Press.	dicular Bonding	Init.	Max.	Av.	dicular Bonding	Init.	Max.	Av.
0.0	32.2	39.5	468	552	522	30.5	350	710	608
10.0	36.8	37.8	385	427	420	32.4	610	840	808
13.3	33.4	33.9	260	320	313	30.3	460	860	742
23.3	35.8	31.9	307	307	307	27.5	580	930	865
33.3	40.5	39.2	247	247	247	32.3	480	850	760
50.0	43.5	41.8	249	249	249	37.4	600	880	793
64.7	44.3	43.4	278	362	326	39.0	580	980	782
82.3	47.7	46.2	336	364	353	44.0	480	730	665
100.0	47.7	50.0	226	226	226	41.2	500	950	788
116.7	48.5	46.0	239	280	265	44.9	550	880	717
133.3	48.0	53.4	275	292	285	46.7	560	1110	870
150.0	47.4	40.5	254	254	254	37.1	550	960	775

The effect of final pressing on six-ply sheets, with basis weights of about 110 pounds, made from unbleached kraft stock with a freeness of 770, is shown in Table XXXI. The data in Table XXXII are the effect of the pressing on the bonding between plies in a two-ply sheet, with a basis weight of about 60 pounds, made from the same stock as the six-ply sheets. The latter were 35.3 per cent dry and the two-ply sheets were 28.0 per cent dry after couching at a pressure of 10 pounds per linear inch. Figure 15 shows the effect of pressing on Mullen strength and Riehle stiffness for the six-ply sheets and on the perpendicular bonding test for the two-ply sheets.

TABLE XXXI

EFFECT OF FINAL PRESSING ON STRENGTH OF SIX-PLY SHEETS OF UNBLEACHED KRAFT--FREENESS 770

Final Pressure	% Dry, Pressed	Appar. Density	Mullen	Tear	Riehle	Tensile
0.0	35.3	3.75	346	11.3	74.1	88.3
10.0	36.5	3.89	360	10.7	69.8	88.7
13.3	36.8	3.88	355	11.8	76.6	76.8
23.3	37.0	3.90	355	11.3	76.0	77.7
33.3	40.2	4.00	358	12.3	79.5	81.9
50.0	42.8	4.06	377	10.9	78.4	85.1
64.7	45.2	4.28	386	11.4	78.1	87.7
82.3	45.4	4.35	388	10.9	83.2	88.4
100.0	46.6	4.52	390	11.4	80.4	84.4
116.7	48.3	4.48	389	10.7	80.7	89.0
133.3	47.6	4.49	398	11.1	82.4	85.9
150.0	48.3	4.53	394	11.2	82.5	94.1

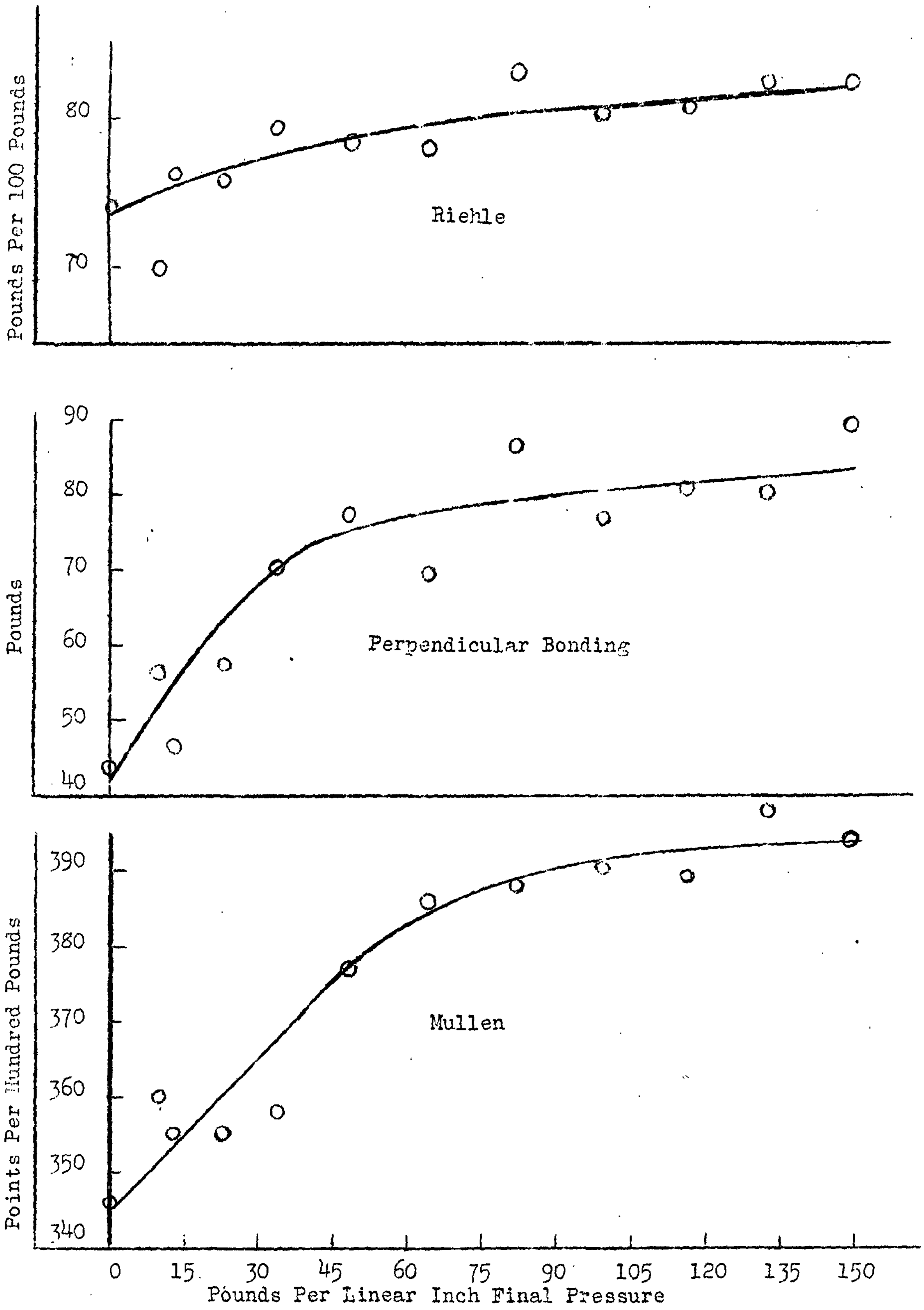


FIGURE 15. EFFECT OF FINAL PRESSURE ON UNBLEACHED KRAFT

TABLE XXXII

EFFECT OF FINAL PRESSING ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF UNBLEACHED KRAFT--FREENESS 770

Final Pressure	% Dry, Pressed	Perpendicular Bond.	Tear Split
0.0	28.0	43.9	17.5
10.0	30.8	56.6	15.3
13.3	29.0	46.6	19.7
23.3	35.6	57.3	16.1
33.3	38.4	70.2	17.0
50.0	41.3	77.5	24.9
64.7	43.6	69.6	20.3
82.3	45.1	86.9	19.3
100.0	47.9	77.0	19.0
116.7	47.1	81.5	20.6
133.3	50.1	80.3	20.4
150.0	51.0	89.8	21.7

The results obtained for six-ply sheets, with basis weights of about 100 pounds, made from news-10% unbleached sulfite stock with a freeness of 425, are given in Table XXXIII. Table XXXIV contains the effect of final pressing on the bonding between plies in a two-ply sheet, with a basis weight of about 55 pounds, made from the same stock. The six-ply sheets were 36.6 per cent dry and the two-ply sheets were 28.4 per cent dry after couching with a pressure of 10 pounds per linear inch. Figure 16 gives the Mullen results for the six-ply sheets and the bonding strength in the two-ply sheets.

TABLE XXXIII

EFFECT OF FINAL PRESSING ON STRENGTH OF SIX-PLY SHEETS OF NEWS-10% SULFITE--FREENESS 425

Final Pressure	% Dry, Pressed	Appar. Density	Mullen	Tear	Riehle	Tensile
0.0	36.6	2.63	130.9	4.1	44.9	41.0
10.0	36.7	2.67	131.9	4.6	45.4	38.3
13.3	32.9	2.65	131.3	4.5	45.1	38.7
23.3	35.5	2.66	130.4	4.4	45.0	39.7
33.3	37.9	2.73	129.9	4.5	44.7	39.1
50.0	41.7	2.79	130.1	4.1	48.0	41.0
64.7	45.4	2.84	126.6	4.5	48.8	42.8
82.3	48.8	2.83	130.7	4.2	46.3	42.1
100.0	47.8	2.85	130.8	4.2	41.6	43.0
116.7	48.6	2.90	133.9	4.7	47.6	44.5
133.3	49.0	2.91	130.9	4.2	47.9	43.3
150.0	51.8	2.94	137.4	4.2	46.9	43.1

TABLE XXXIV

EFFECT OF FINAL PRESSING ON BONDING BETWEEN PLIES IN TWO-PLY SHEETS OF NEWS-10% SULFITE--FREENESS 425

Final Pressure	% Dry, Pressed	Perpendicular Bond.	Tear Split
0.0	28.4	22.0	8.7
10.0	31.0	32.0	10.2
13.3	31.7	28.7	8.2
23.3	32.4	28.1	9.5
33.3	37.9	25.8	9.4
50.0	43.7	31.0	10.4
64.7	46.0	38.6	9.9
82.3	50.0	32.6	11.2
100.0	53.4	32.9	16.1
116.7	52.1	34.6	11.0
133.3	53.5	32.7	10.6
150.0	57.5	37.8	12.8

Table XXXV shows the effect of final pressing on a two-ply sheet, the top ply of which is unbleached sulfite stock having a freeness of 595, the bottom ply of which is news-10% unbleached sulfite stock with a freeness of 255.

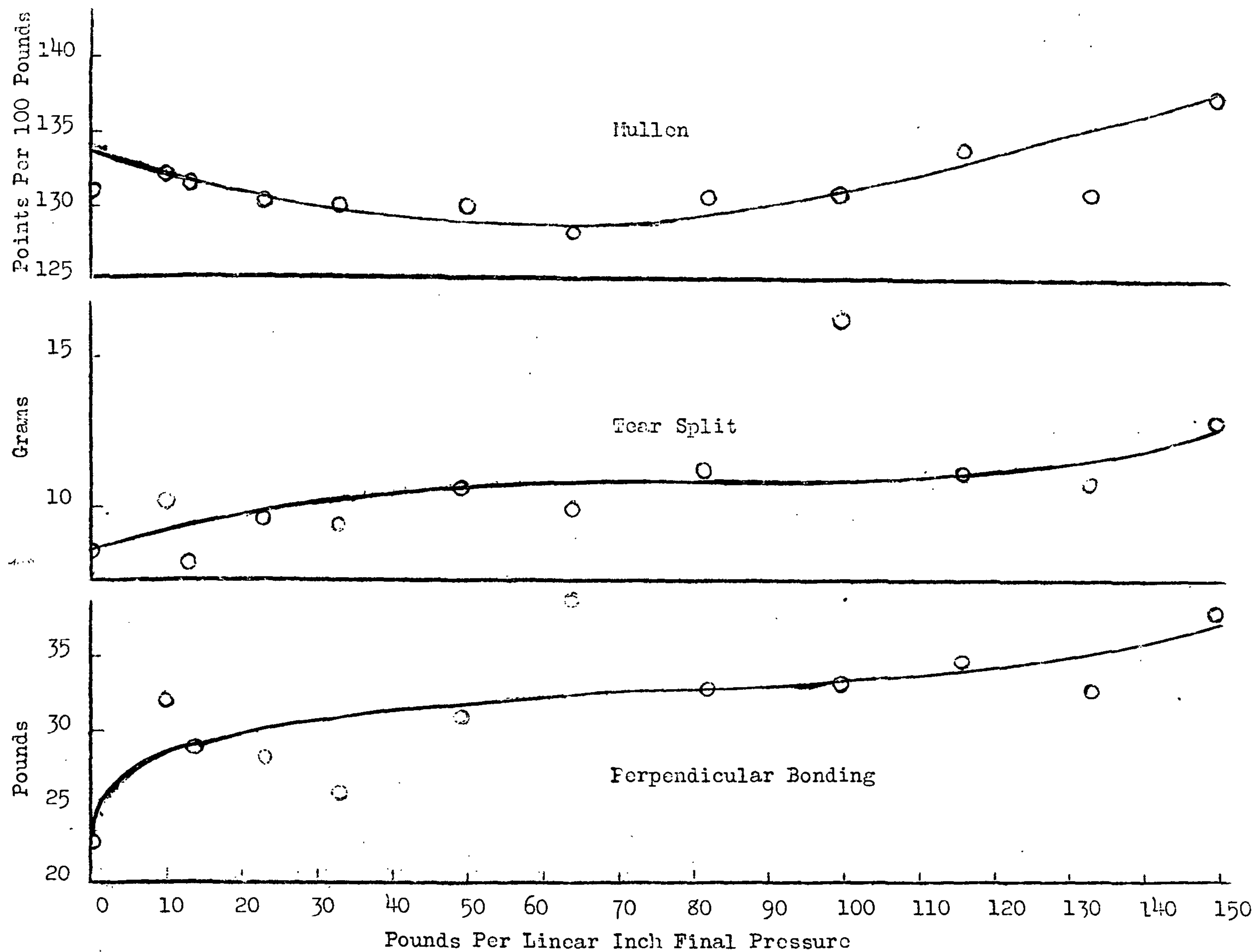


FIGURE 16. EFFECT OF FINAL PRESSURE ON NEWS-SULFITE

Both plies are the same weight, the over-all weight of the sheet being about 63 pounds per thousand square feet. All sheets were couched at 3.3 pounds per linear inch pressure and were 20.6 per cent dry after couching. The Mullen, tear, tensile, and Riehle results are graphed in Figure 17, while the bonding results are shown by Figure 18.

TABLE XXXV

EFFECT OF FINAL PRESSING ON PROPERTIES OF A MIXED TWO-PLY SHEET

Final Press.	% Dry, Press.	App. Dens.	Mullen	Tear	Riehle	Tensile	Stretch	Perpendicular Bonding	Tear Split
0.0	20.6	2.48	172	7.4	46.9	52.4	3.90	27.7	11.9
3.3	22.8	2.55	169	7.2	41.5	50.7	3.88	12.9	7.0
6.7	25.3	2.72	179	7.0	41.1	51.5	3.66	14.5	8.6
11.7	25.4	2.75	192	6.9	43.9	55.2	3.86	31.2	11.8
16.7	30.1	2.96	188	6.9	47.8	56.0	3.72	37.0	13.9
22.3	32.2	3.04	193	6.8	48.8	57.4	4.00	37.8	12.8
33.3	35.6	3.10	196	6.9	52.1	60.6	3.98	40.5	13.1
43.3	36.3	3.18	207	6.7	50.9	61.4	3.62	41.7	14.3
56.7	39.6	3.29	200	7.1	52.5	62.2	3.81	42.0	14.1
70.0	42.2	3.37	209	6.7	51.7	62.6	4.28	43.4	15.3
83.3	43.9	3.42	202	6.8	51.8	62.0	3.86	42.4	15.6
100.0	44.1	3.50	216	6.7	51.4	67.5	3.88	42.5	15.6
116.7	45.4	3.54	214	6.5	51.4	65.7	3.96	42.2	15.4
133.3	46.4	3.49	212	6.5	49.7	63.7	3.94	41.8	15.1

For all stocks and at all freenesses, increasing the final pressure caused an increase in the bonding between plies. The rate of increase was greater at the lower pressures so that the bonding tended to approach a constant value for the higher pressures.

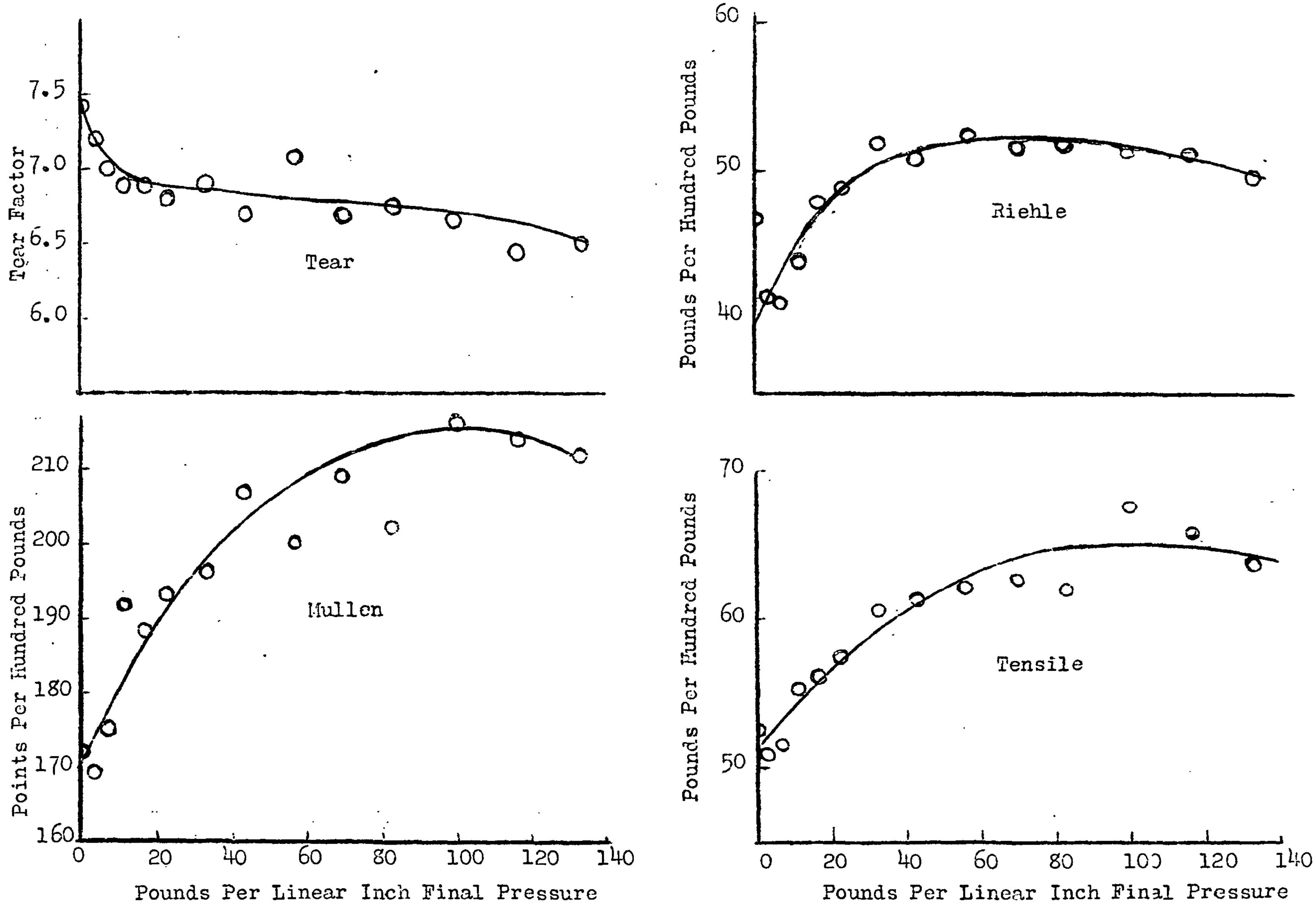
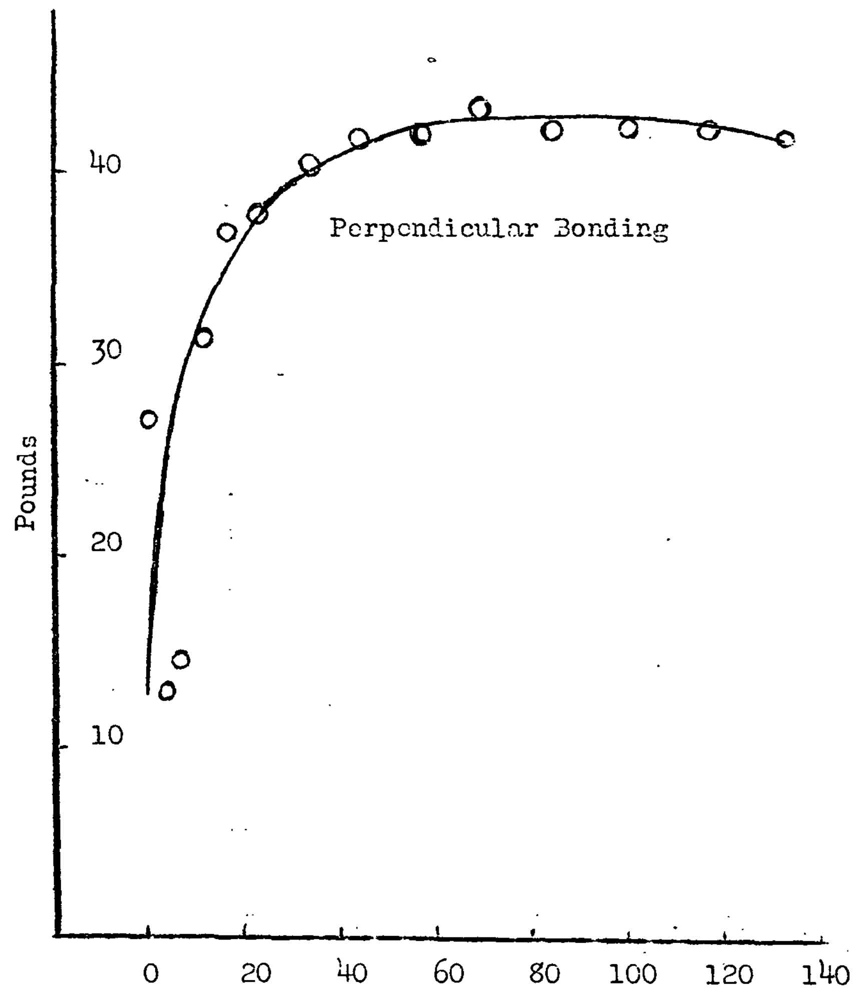


FIGURE 17. EFFECT OF FINAL PRESSURE ON TWO-PLY NEWS--SULFITE



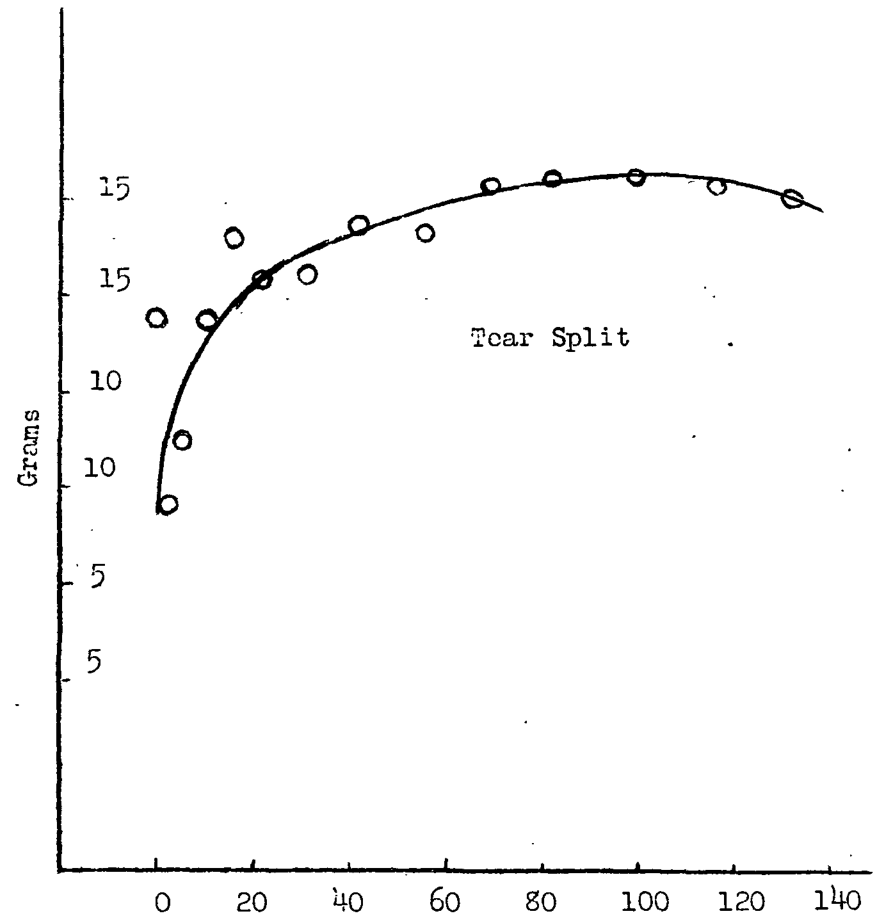


FIGURE 18. EFFECT OF FINAL PRESSURE ON TWO-PLY NEWS--SULFITE

This constant value will be reached at a lower pressure if the stock is fibrillated than if it is coarse. This is possible, since the coarser stock depends primarily on the pressing to give sufficient contact between plies so that a good bonding may result.

The tear split and the perpendicular bonding tests showed good agreement in measuring the bonding force with changes in the amount of pressing. The tearing-type splitting test (using the Forman tester) indicated a maximum in the bonding between two plies of unbleached sulfite with a freeness of 595. This maximum occurred at a relatively low pressure, viz., around 40 pounds per inch. It was about this pressure that the tear split and the perpendicular bonding tests showed a flattening out of the increase in bonding, but they did not go through a maximum. It is believed that the maximum obtained with the Forman tester resulted from some action peculiar to the tester and not from an actual maximum in the bonding; perhaps the way the sheet tears apart during testing affects the test.

It is apparent that, for stocks that are relatively well beaten, the optimum amount of pressing required to bond the sheet together is fairly low, being in the range of 40 to 50 pounds per linear inch.

As the amount of final pressing was increased, the Mullen strength of the sheet increased for all the stocks studied except unbleached sulfite with a freeness of 530. The Mullen would be expected to rise with increasing wet-pressing of the sheets and increasing bonding between plies, as pointed out for the effect of couching pressure.

It is believed that the bursting strength for the sulfite at a freeness of 530 can be traced back to a crushing action during pressing. This stock was relatively very wet after it was couched with the low pressure used. When light final pressing was employed, the sheet was changed little with respect to the bonding between fibers in the plies and therefore the Mullen test remained nearly constant. However, as the final pressing was increased, it was increasingly difficult for the water to be removed from the sheet rapidly enough, resulting in a disturbance of the sheet structure, which in turn produced the lower Mullen strength; however, such an action apparently does not overcome the effect of pressing on the bonding between plies.

An inspection of the density data in Table XXVII shows that something unusual happened to the sheet structure as the pressing was increased, for there was very little increase in the density of the sheet with a relatively large increase in pressure. This cannot be due to the fact that the sheet is already as dense as it can be, for the apparent density of the sheets made from the same pulp at a freeness of 735 (<u>see</u> Table XXIX.) increased with pressure at the density at which the sulfite with a freeness of 530 was relatively constant.

Due to this crushing-type action, the flexural stiffness of the sheets should be lowered and this was actually the case, as shown by the Suvant test. The Riehle stiffness might also be expected to decrease, but only if the long direction of the test sample were parallel to the line of crushing in the sheet, i.e., across the direction of passage of the sheet between the press rolls; however, the test samples were cut in the opposite direction, so that the test did not show the decreased stiffness. The Suvant test strips were cut with their long direction in the direction of motion between the rolls.

In other cases, the stiffness of the sheets increased with pressure, as might be expected for the denser sheet and the increased bonding. When an all-news sheet was used, the stiffness increased but little because of the slight change in the density and bonding brought about by the pressing. The Riehle stiffness closely paralleled the bursting strength and, like the bursting strength and the bonding between plies, it tended to reach a maximum value and then to remain constant for sheets made from fibrillated stock.

The tearing strength of the multi-ply sheets was not affected by increasing the amount of final pressing, whereas that of the thin single sheets decreased with increasing wet-pressure. Instead of the line-type tear obtained for thin sheets, a splitting-type tear was obtained for the multi-ply sheets. The latter type is not as sensitive to changes in the sheet.

The sharp decrease in the tearing strength for the sulfite—news sheet at low pressures is due to this splitting tear for, as the sheet becomes a little less bulky with the increasing pressure, the tear becomes a little more nearly line-type. The nature of the tear also accounts for the variations obtained in any series of tests.

The tensile strength of the sheets behaved very much as the bursting strength, increasing as the pressure was increased, as also found by Doughty (1,2). It would appear, however, that a very large range of pressures must be used to cause an increase in tensile strength similar to that caused by a moderate amount of beating, because at the higher pressures, the rate of increase in tensile becomes nearly zero.

Summarizing, an increase in final pressing results in an effect similar to that produced by a small amount of beating; the bursting strength, stiffness, and bonding between plies become greater as the amount of pressing is increased. However, above a pressing force of about 50 pounds per inch, the increase is a small one. An exception in the behavior of these properties (excluding bonding) is encountered when the sheet is wet enough at the time of pressing so that it would crush slightly.

Effect of Calendering on the Strength and Bonding

Some preliminary work on calendering indicated that it might decrease the strength and bonding between plies to an appreciable extent.

The results of some of this preliminary work are given in Table XXXVI. The sheets used were two-ply sheets (basis weight 58.6 pounds) made from unbleached sulfite with a freeness of 595. They were couched at 3.3 and pressed at 86.3 pounds per linear inch pressure. One set of sheets was calendered by passing the sheet four times through rolls, weighted to give a force of 150 pounds per inch' the other set was uncalendered.

TABLE XXXVI

EFFECT OF CALENDERING ON PROPERTIES OF UNBLEACHED SULFITE

	Uncalendered	Calendered
Apparent density..........	4.05	5.31
Perpendicular bonding.....	48.0	41.8
Tear split................	21.1	18.3
Tensile tester		
Initial................	74	54
Maximum................	79	61
Forman tester		
Initial................	293	221
Maximum................	335	280
Average................	324	270

The results of further preliminary work are given in Table XXXVII. The sheets used in this case were two-ply sheets, with a basis weight of about 64 pounds, the top ply being unbleached sulfite and the bottom ply news-10% unbleached sulfite, as described in the previous section.

TABLE XXXVII

EFFECT OF CALENDERING ON PROPERTIES OF TWO-PLY NEWS-10% SULFITE--UNBLEACHED SULFITE SHEETS

Final Press.	App. Dens.	Mullen	Tear	Riehle	Tensile	Stretch	Perpendicular Bonding	Tear Split
Uncalendered								
0.0	2.48	172	7.4	46.9	52.4	3.90	27.7	11.9
33.3	3.10	196	6.9	52.1	60.6	3.98	40.5	13.1
133.3	3.49	212	6.5	49.7	63.7	3.94	41.8	15.1
Calendered								
0.0	3.12	157	5.5	31.5	48.6	3.60	5.5	4.9
33.3	3.56	191	5.6	41.9	56.0	3.84	32.7	15.0
133.3	3.90	208	5.5	43.0	61.5	3.80	36.0	15.2

A more complete study was then undertaken to study the effect of calendering. The sheets used were two-ply sheets, with basis weights of about 64 pounds, made from unbleached sulfite with a freeness of 620. The sheets were couched at 3.3 and pressed at 66.7 pounds per inch. Both the calendering pressure and the number of passes at a given pressure were varied. Table XXXVIII shows the effect of different calendering pressures for four passes through the rolls. Figure 19 represents some of these results graphically. Table XXXIX shows the effect of the number of passes at a calendering pressure of 112.5 pounds per inch. Part of these results is presented in Figure 20.

TABLE XXXVIII

EFFECT OF CALENDERING PRESSURE ON TWO-PLY SHEETS OF UNBLEACHED SULFITE

Press.	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpendicular Bonding	Tear Split
0.0	3.98	336	8.4	61.0	64.5	83.5	7.00	45.1	24.5
11.3	4.06	326	8.8	56.5	65.2	83.4	6.98	33.7	23.9
22.5	4.09	323	8.4	61.0	78.0	86.2	7.44	38.5	24.1
33.8	4.14	332	8.7	59.9	75.9	81.6	6.50	37.2	27.0
45.0	4.22	324	8.7	58.9	70.9	84.4	6.54	35.5	24.9
60.0	4.20	329	8.3	57.6	72.0	86.6	7.36	47.1	26.1
75.0	4.22	324	8.5	56.7	66.0	86.3	6.60	31.6	24.7
93.7	4.30	327	8.2	54.8	59.8	83.9	6.52	34.3	22.3
112.5	4.34	336	7.9	52.5	60.6	84.9	6.78	40.9	25.3
131.3	4.36	318	8.1	50.1	57.9	81.6	6.66	32.3	22.1
150.0	4.33	323	8.1	49.9	59.7	82.4	6.22	52.1	22.5

TABLE XXXIX

EFFECT OF THE NUMBER OF PASSES THROUGH CALENDER ROLLS ON TWO-PLY SHEETS OF UNBLEACHED SULFITE

No. of Passes	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpendicular Bonding	Tear Split
0	3.98	336	8.4	61.0	64.5	83.5	7.00	45.1	24.5
1	4.20	331	8.5	52.4	73.8	83.8	6.78	48.5	26.7
2	4.21	306	8.5	52.8	65.6	81.2	6.52	49.8	25.0
3	4.26	318	8.2	52.4	65.1	85.1	6.42	39.6	22.2
4	4.34	336	7.9	52.5	60.6	84.9	6.78	40.9	25.3
6	4.30	330	8.1	53.1	61.6	85.1	6.62	38.1	22.2
9	4.32	324	8.1	50.0	60.0	83.5	6.90	42.6	23.6
13	4.44	319	8.0	48.4	57.7	81.9	8.24	40.9	24.3

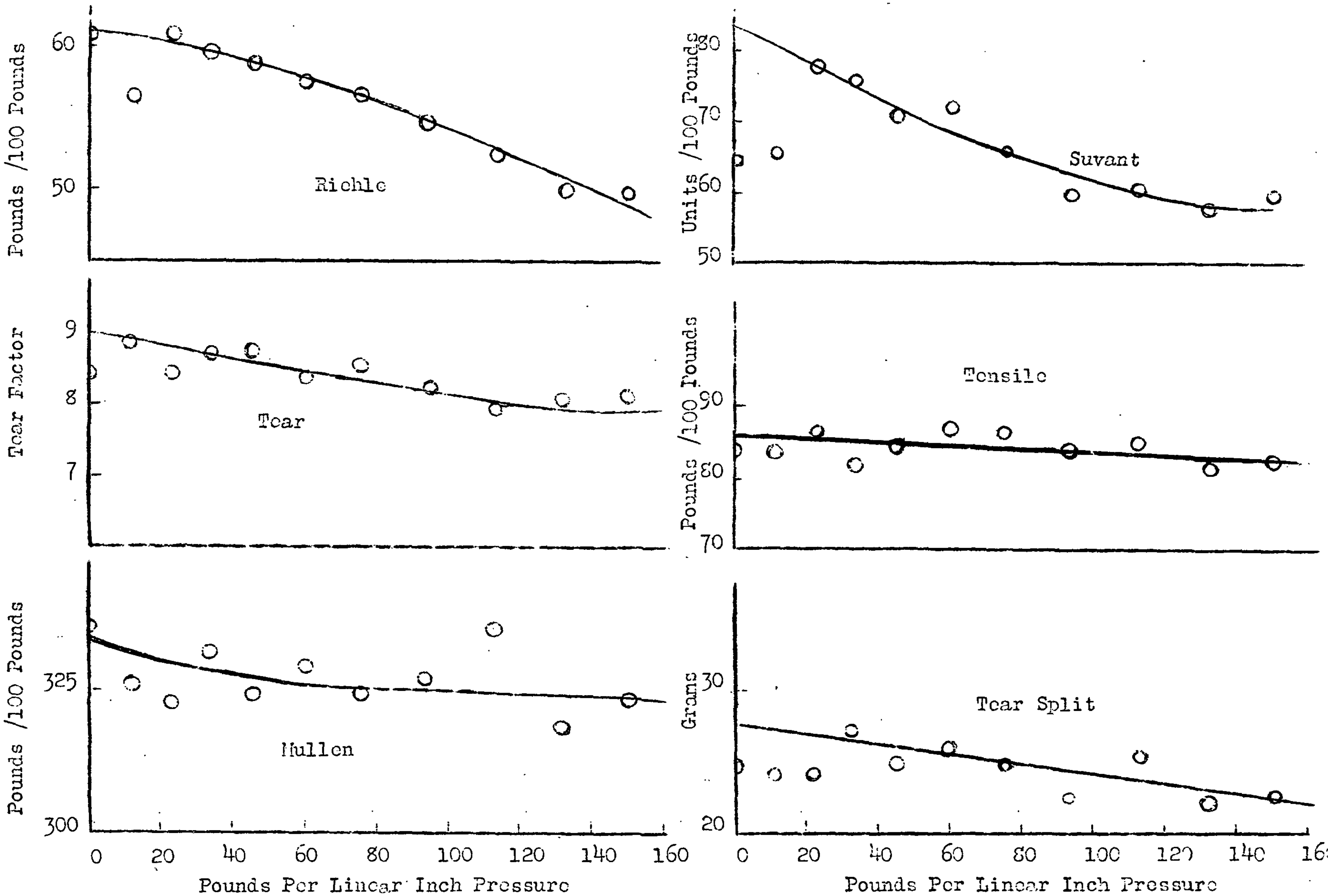


FIGURE 19. EFFECT OF CALENDERING PRESSURE ON UNBLEACHED SULFITE

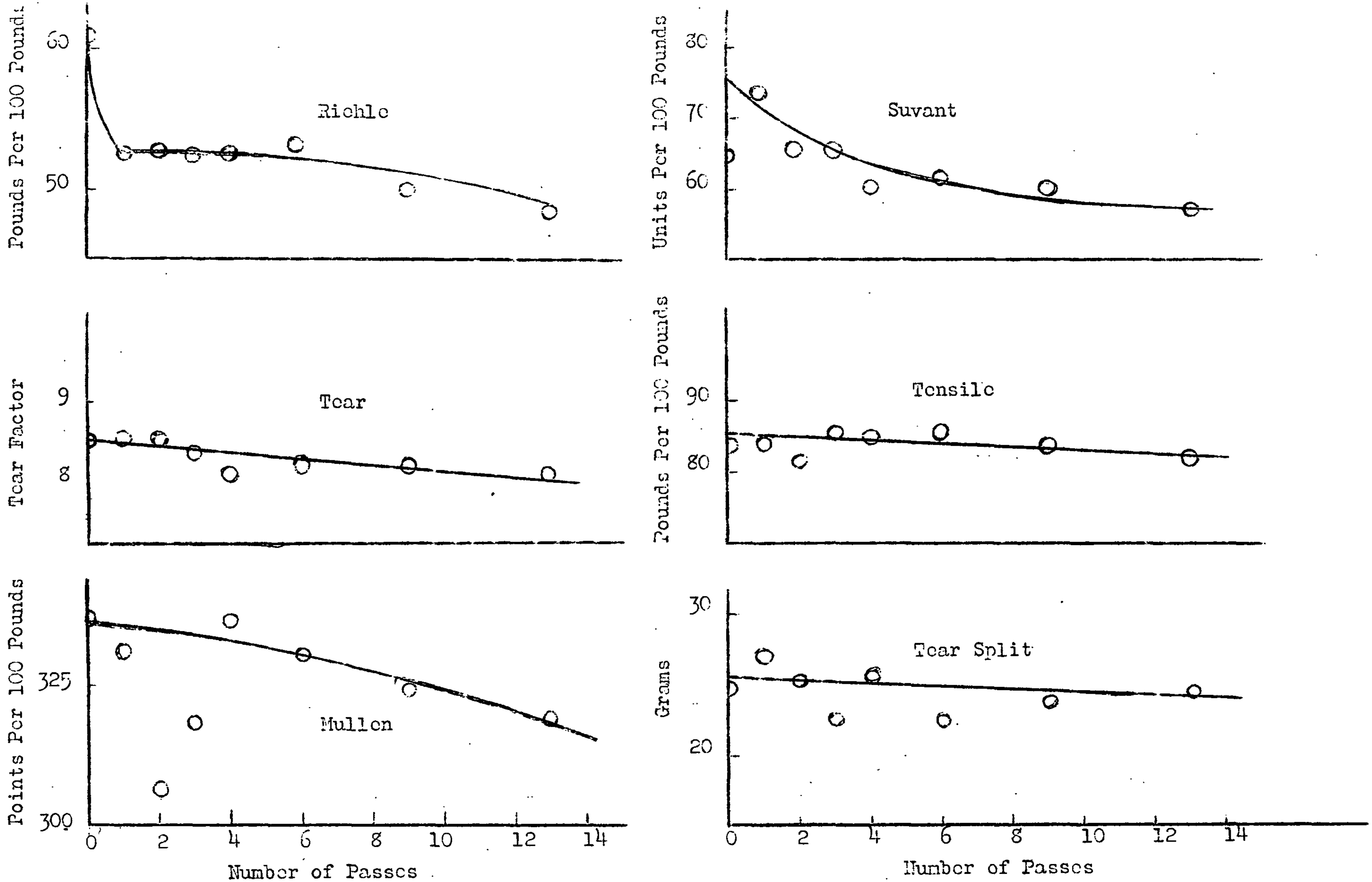


FIGURE 20. EFFECT OF THE NUMBER OF CALENDERING PASSES

Thin single sheets, with a basis weight of 13.2 pounds, were also calendered by passing them six times through the rolls weighted to give a force of 150 pounds per inch. The results obtained on these sheets were compared with those obtained on similar sheets before calendering. The sheets were made from unbleached sulfite stock with a freeness of 620. They were wet-pressed at a pressure of 66.7 pounds per linear inch. Table XL summarizes the results obtained.

TABLE XL

EFFECT OF CALENDERING ON SINGLE SHEETS
OF UNBLEACHED SULFITE

	Uncalendered	Calendered
Apparent density.........	2.52	3.56
Mullen..................	236	206
Tear....................	4.61	3.79
Suvant..................	9.7	8.0
Riehle..................	25.4	22.4
Tensile.................	84.1	83.6
Stretch.................	3.04	2.82
Perpendicular bonding....	75.6	60.5

Calendering a sheet, whether it be a single sheet or a multi-ply sheet, reduces the strength of the sheet. The reduction in all strength tests but stiffness is small for the calendering conditions studied, if the sheet is well bonded before calendering. However, if the sheet is only loosely bonded originally, calendering at 150 pounds per inch causes a large decrease in both strength and bonding.

Although the Mullen strength of a well bonded sheet is reduced only slightly, the stiffness is reduced markedly as the amount of calendering is increased. Both the Riehle and Suvant tests showed this. It might be expected that the increased sheet density would cause a stiffer sheet to be obtained, as it does when the density is increased by wet-pressing. Since this was not the case, it would appear that the "solid fraction" of the sheet need not, as stated by Doughty (1,2), govern the strength tests of the sheet.

Bekk (12,13) pointed out that supercalendered sheets have a surprisingly low pick test. This he attributed to the "grinding action of the calender rolls". It is the crushing action during calendering that causes the fibers to lose their resilience, and therefore, the sheet decreases in stiffness. The bursting and tensile strengths were less for the calendered sheets, due to loss of resilience and a reduction in the bonding between plies and between fibers in the plies. The tearing strength decreased with increasing calendering pressure, because the denser sheets tore more nearly in a line.

From these results it may be seen that the less calendering that is required to obtain a given finish on board, the better the sheet and that any treatment which will give the sheet a better surface before it reaches the calenders will produce a sheet with greater stiffness, greater yardage, and better strength. For any given caliper and finish, reducing the amount of calendering improves the major properties of a board sheet.

Effect of Drying on Strength and Bonding

This work was carried out in order to determine the effect of the moisture content of the final sheet on the bonding and strength tests, both at the moisture content at which the sheets left the drier and after these sheets had come to equilibrium with air at a temperature of 70° F. and a relative humidity of 65 per cent.

The sheets were made from unbleached sulfite with a freeness of 585, couched at 3.3 pounds per inch and pressed at 66.7 pounds per inch. The sheets were 21.5 per cent dry after couching and 39.4 per cent dry after pressing. The basis weight of the sheets was approximately 58 pounds on an oven-dry basis.

Sets of five identical two-ply sheets were prepared, and dried at 105° C. on the Noble and Wood, the amount of drying being determined by the number of passes through the drier. As soon as the sheets came off the drier, those to be seasoned were put in the humidity room, and those to be tested at the moisture content at which they left the drier were cut up immediately and placed in air-tight containers and allowed to stand overnight. The unseasoned sheets were tested as rapidly as possible so that the moisture content would change but little.

Although the perpendicular bonding test is not applicable to testing sheets at a given moisture content, due to the addition of water with the adhesive and the subsequent seasoning, it was used on both the seasoned and unseasoned sheets. For the unseasoned sheets, the blocks were allowed to remain 72 hours after the sheets were cemented between them; 20 hours were allowed for the seasoned sheets. All test samples appeared dry to the touch when the assembly was pulled apart.

Table XLI and Figures 21, 22, and 23 present the results.

TABLE XLI

EFFECT OF DRYING ON THE PROPERTIES OF TWO-PLY SHEETS OF UNBLEACHED SULFITE

No. of Passes	% Dry, Tested	Mullen	Tear	Tensile	Stretch	Riehle	Suvant	Perpendicular Bonding	Tear Split
Unseasoned									
0	39.4	57	3.4	7.5	7.86	3.2	9.5	28.2	2.3
1	50.9	85	4.6	16.2	7.94	7.0	14.7	21.2	4.2
2	68.0	199	8.1	46.6	8.90	16.5	29.9	47.5	10.7
3	85.1	368	10.1	97.8	8.96	41.5	67.5	62.6	20.3
4	92.0	373	8.8	107.1	6.12	65.0	----	67.0	18.2
5	95.6	335	7.4	116.9	5.70	80.4	80.3	65.8	18.7
6	96.8	322	7.1	121.0	5.58	85.2	85.2	71.9	19.4
Seasoned									
0	89.6	407	10.0	106.1	8.04	56.9	81.0	72.3	23.9
1	89.6	404	10.4	110.0	8.26	41.0	80.4	66.4	27.7
2	90.2	388	9.6	108.9	7.98	45.3	83.8	70.5	22.7
3	89.5	366	10.0	101.3	7.38	44.7	89.6	65.8	21.8
4	90.2	366	9.0	101.1	6.64	46.3	72.2	62.6	18.0
5	90.7	370	9.3	102.7	6.70	50.2	79.8	60.9	22.2
6	90.9	360	9.6	106.2	6.22	49.8	90.9	59.6	20.0

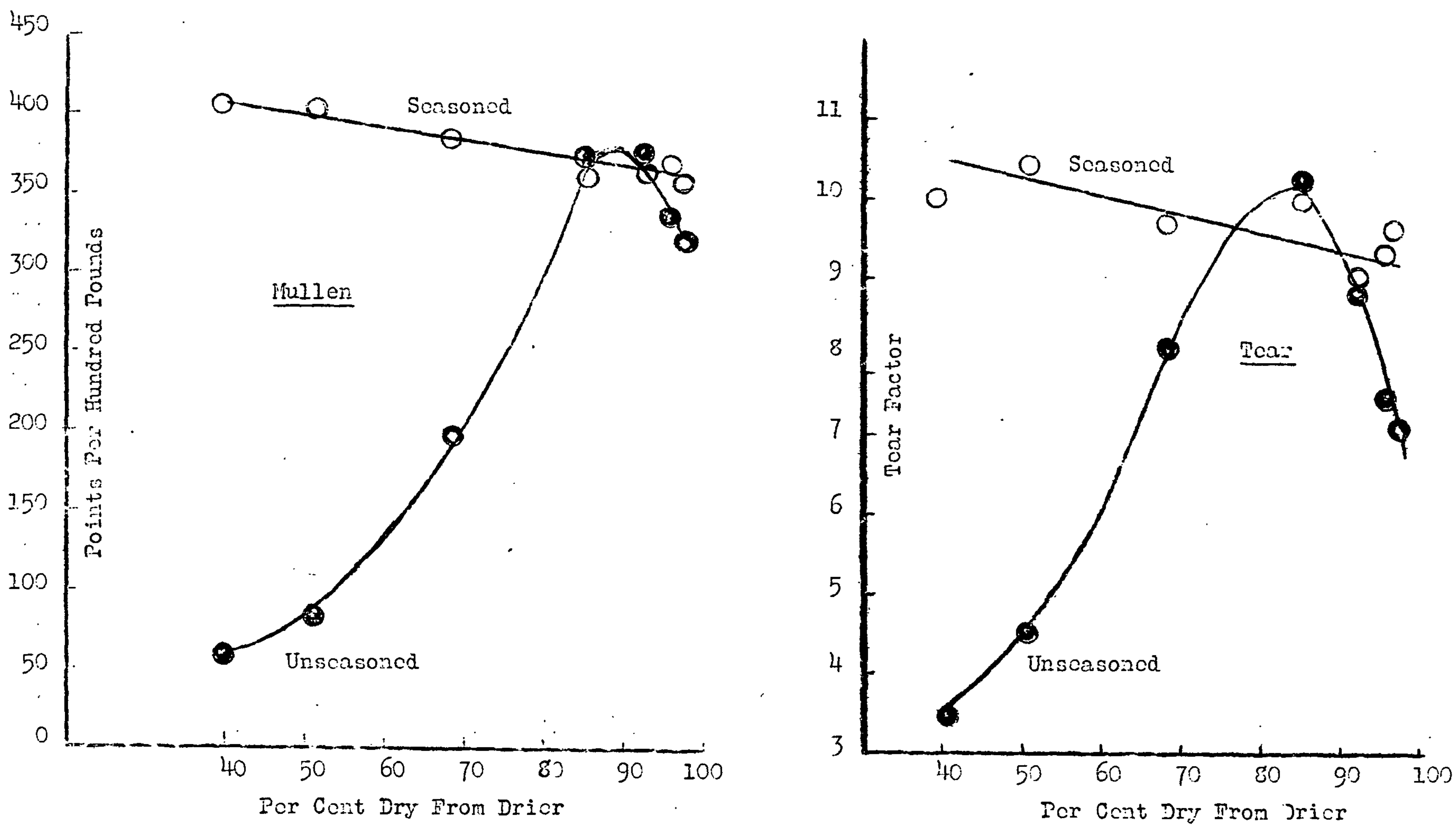


FIGURE 21. EFFECT OF DRYING

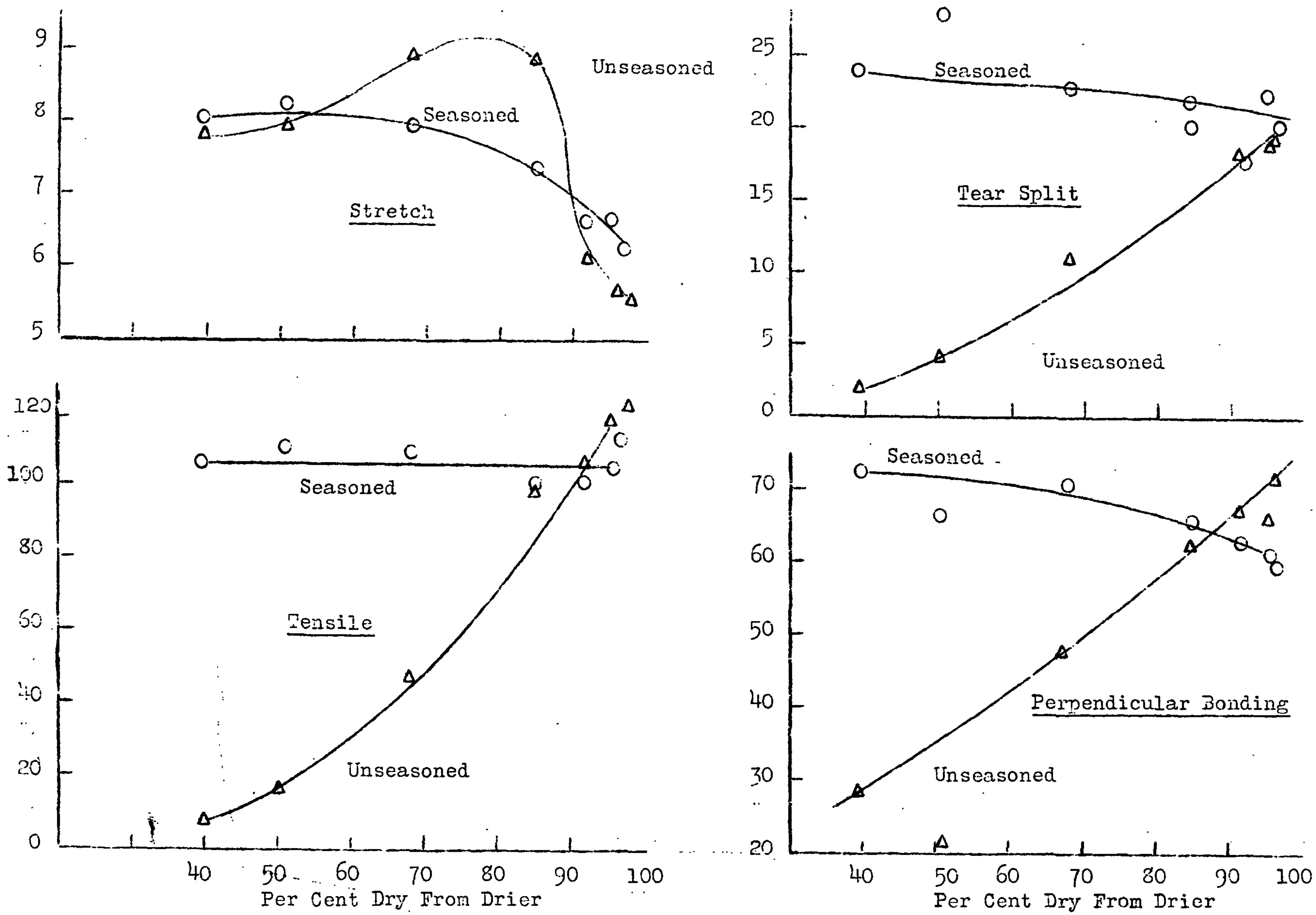


FIGURE 22. EFFECT OF DRYING

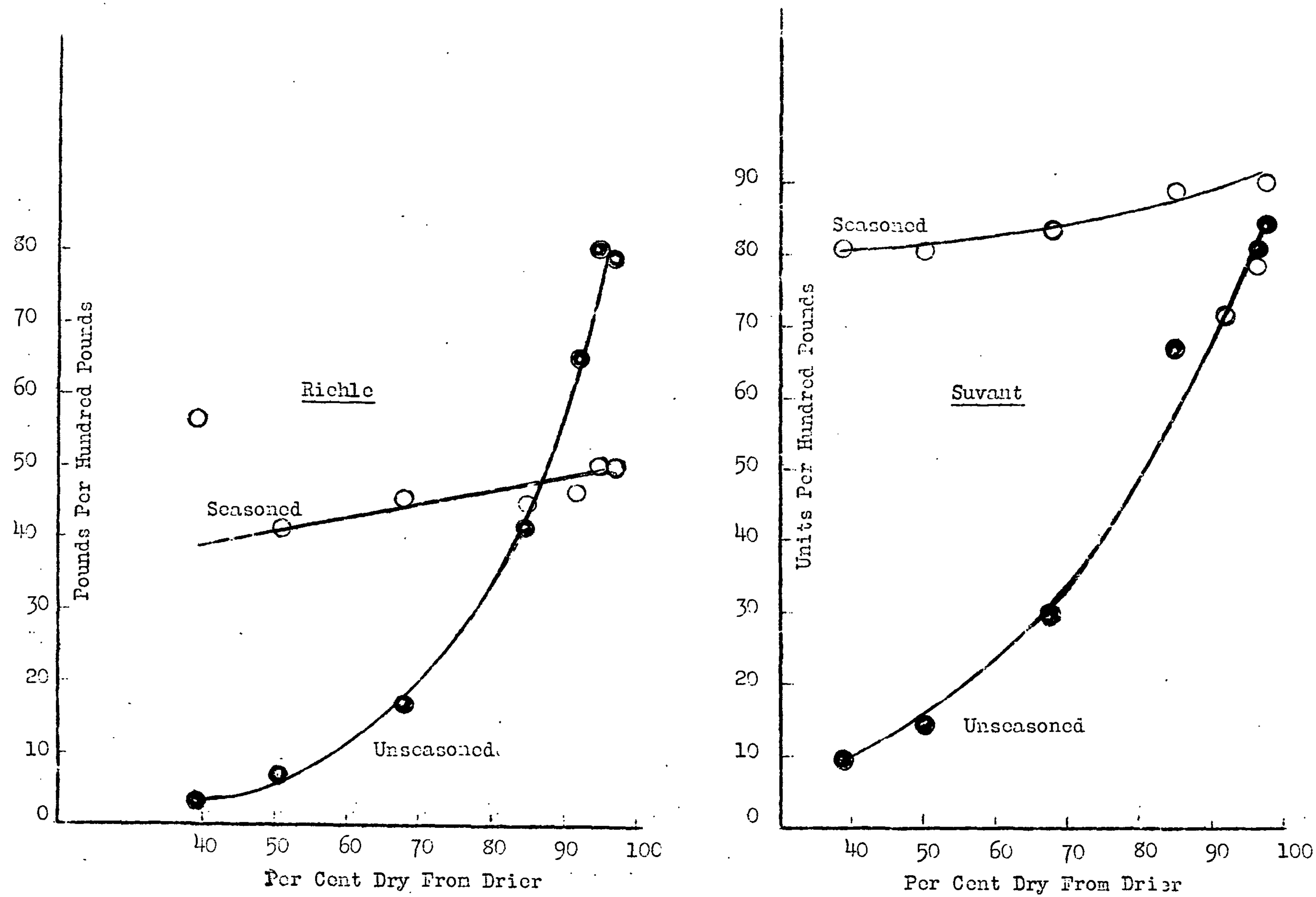


FIGURE 23. EFFECT OF DRYING

It is apparent that both the amount of drying and the moisture content of the sheets at the time of testing play important roles in determining the strength properties and the strength of the bonding between plies in a multi-ply sheet. The tests are affected more by the moisture content of the test sample than by the amount of drying given the sheet.

As the amount of moisture in the sheet is reduced, the bonding between plies, as measured by both the perpendicular bonding and the tear split tests, increases regularly by an almost linear relationship. On the other hand, when the sheets are allowed to come to the same equilibrium moisture content, the bonding between plies is found to be slightly lower for the sheets that have been dried the most.

Drying the sheets too much caused a reduction in the elasticity of the fibers and the cementing structure between the fibers and plies; however, the strength of the bond is not decreased by this change in elasticity but increased. Since the tensile strength of the sheet constantly increases as the amount of drying increases, it is apparent that the fibers cannot be pulled apart as readily at the lower moisture contents. This, as well as the increasing strength of bonding between plies, shows that, although the removal of water from the sheet results in a decreased amount of stretch, the strength of the bond becomes greater. Although the structure cementing the plies and fibers together becomes more brittle, it retains its strength when the water of hydration is removed.

Since the Mullen strength is dependent on the extensibility of the sheet, it passes through a maximum at very nearly the same moisture content as that at which the stretch goes through a maximum when the moisture content of the sheets at the time of testing is decreasing. On the other hand, when the sheets have been dried to different moisture contents, and then all brought to the same moisture content by seasoning before testing, the bursting strength decreases linearly with increasing drying. The decrease is relatively small, being caused by the loss in the extensibility of the fibers and not by a decreasing tensile strength, for this is practically constant. The adsorption of water on the fibers as the more completely dried sheets season is not sufficient to make up completely for the loss of that removed from the sheet structure when it is dried too much.

The bonding between plies decreases slightly for the seasoned sheets as the amount of drying that they have undergone before seasoning is increased. The curves show that, by drying the sheets gradually to a moisture content of 10 per cent, a bond results which is as strong as that obtained by rapidly drying the sheets to a moisture content of 3 per cent. However, it is apparent that, for the sheet and stock studied, the drying operation does not cause pockets of steam to be formed at the interface between plies, which would reduce the bonding.

Sheets dried rapidly to below 10 per cent moisture content lose some of their bonding strength as the amount of water in the cementing structure is increased by seasoning. The bonding in the seasoned sheets is nearly the same as that of the unseasoned sheets dried to the moisture content possessed by the seasoned sheets.

The greater the amount of drying, the greater the stiffness of the sheet, even after seasoning, again pointing to a decreased resilience or elasticity of the fibers and the bonding structure between the fibers and the plies. For seasoned sheets, the stiffness increases only a little as the amount of drying before seasoning is increased.

The tearing strength also passes through a maximum at the point where the stretch of the sheet is a maximum. Beyond this point, as the sheets are dried more, the fibers more easily shear off in the tearing test, because the moisture content becomes so low that the fibers become brittle and break easily when a shearing force is applied. Further, with the lower resilience, the tear is more in a line and the value is less.

The following conclusions may be drawn from this section:

For unseasoned sheets, increasing the amount of drying given a two-ply sheet causes an increase in the bonding between plies over the range of 60 to 3 per cent moisture content. At first, it increases the stretch of the sheet, but as the lower moisture contents are approached the sheet loses a part of its stretch and becomes more brittle. The tensile strength increases linearly with the amount of drying. The result of these two effects is a maximum in the bursting strength at the point where there is a maximum in the stretch. The decreasing moisture content of the sheets results in an increasing stiffness of the sheet, causing both the Suvant and Riehle stiffness values to increase regularly with decreasing moisture content. Due to the increasing brittleness of the fibers at the lower moisture contents, the tearing strength also passes through a maximum.

For seasoned sheets, the amount of drying before seasoning has an effect on the strength of the sheets, although the effect is not large. All the results can be related directly to the increased brittleness or stiffness of the sheets when dried to the lower moisture contents. Apparently absorption of water during seasoning is not sufficient to replace that originally present before drying.

Effect of Beating on Strength and Bonding

As the work progressed, it became apparent that the amount of beating given a stock plays a very important role in determining the strength of the bonding between plies.

In fact, it appeared that beating could increase the bonding by a very large amount.

Therefore, the effect of beating on both bleached and unbleached sulfite and the effect of milling in a pebble mill on the unbleached sulfite were determined.

The sheets made to carry out the study for the bleached sulfite consisted of thin single sheets with a basis weight of about 12.6 pounds (about 43 pounds on a 25 x 40--500 basis), and heavy two-ply sheets with a basis weight of about 65 pounds.

Several sheets were used to carry out the study of the beater run on unbleached sulfite: thin single sheets with a basis weight of about 13 pounds, thick single sheets with a basis weight of about 53 pounds, heavy two-ply sheets with both plies the same, heavy two-ply sheets with the top ply made from stock with a freeness of 775, and heavy two-ply sheets with the bottom ply made from stock with a freeness of 380; all two-ply sheets had a basis weight of about 68 pounds.

The sheets made for the pebble mill run on the unbleached sulfite were thin single sheets with a basis weight of about 14 pounds, thick single sheets with a basis weight of about 64 pounds, and heavy two-ply sheets with a basis weight of about 70 pounds.

All single sheets were pressed with a force of 66.7 pounds per inch and dried in contact with the wire upon which they were formed and pressed. The two-ply sheets were couched with a force of 3.3 and pressed with a force of 66.7 pounds per inch. They were not dried in contact with the wire.

The results obtained for the beater run on the bleached sulfite, using the thin single sheets, are presented in Table XLII; the results obtained on the two-ply sheets are presented in Table XLIII. The bursting and bonding strengths for both types of sheets are shown by Figure 24.

TABLE XLII

EFFECT OF BEATING ON BLEACHED SULFITE--SINGLE SHEETS

Minutes	Free-ness	App. Dens.	Mullen	Fold	Tear	Tensile	Stretch	Perpen-dicular Bonding
0	850	2.44	40	0	4.63	19.6	1.89	7.7
60	775	2.96	219	107	5.25	70.5	3.47	45.4
95	550	3.19	320	961	3.70	98.5	3.82	81.3
115	415	3.20	326	722	3.99	106.2	3.62	77.6
135	360	3.22	340	735	4.00	97.6	3.71	85.9
155	280	3.14	304	810	3.56	93.9	3.78	87.4
190	190	3.01	293	1153	3.54	103.1	3.61	90.0

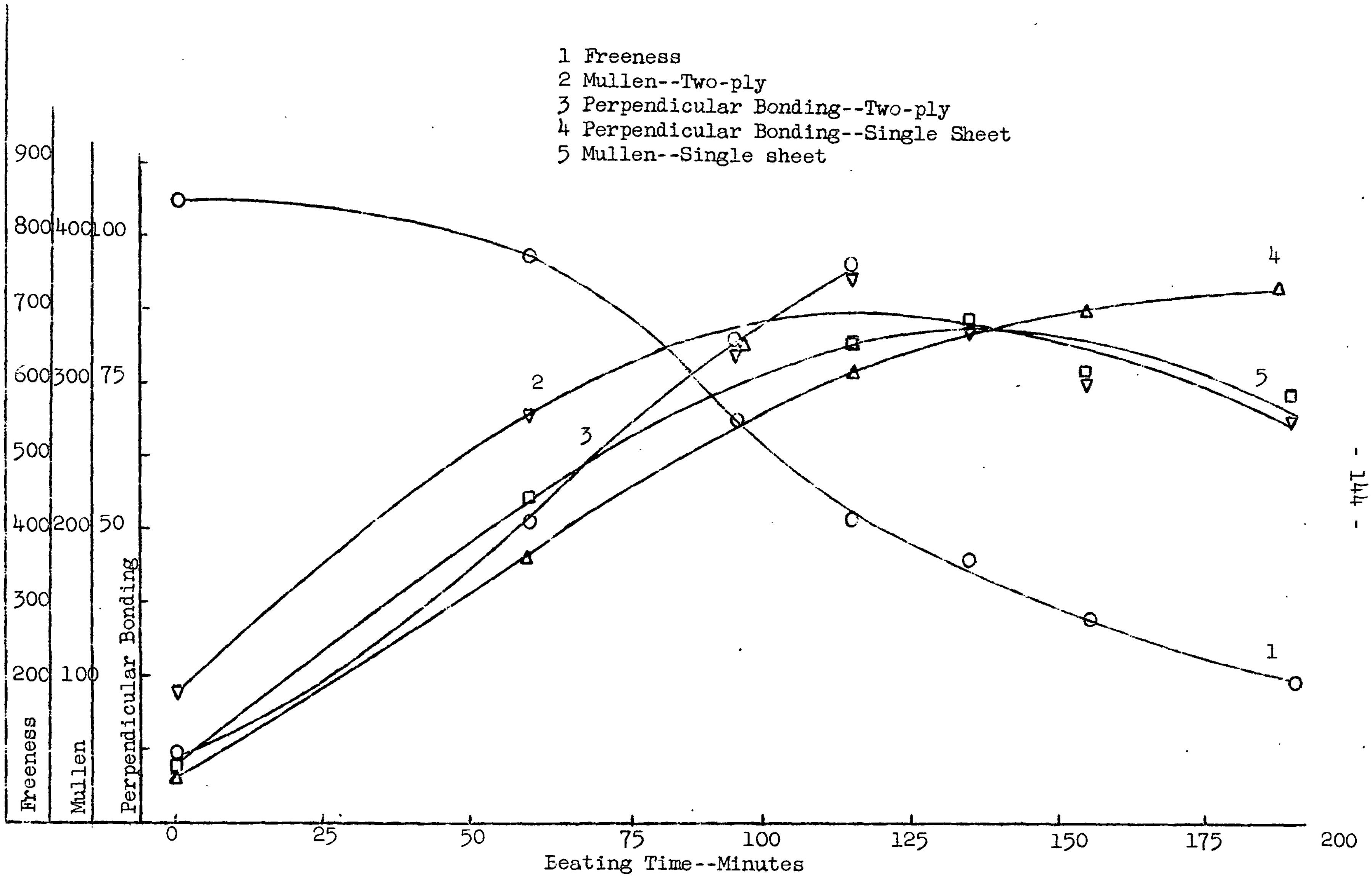


FIGURE 24. EFFECT OF BEATING ON BLEACHED SULFITE

TABLE XLIII

EFFECT OF BEATING ON BLEACHED SULFITE--TWO-PLY SHEETS

Minutes	Freeness	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpendicular Bonding	Tear Split
0	850	3.19	89	5.9	22.7	54.7	30.2	4.08	11.7	10.9
60	775	4.06	279	8.0	49.5	67.2	75.0	5.52	51.5	17.9
95	550	4.15	320	7.7	54.6	56.1	87.5	7.92	82.5	28.9
115	415	4.18	370	8.1	61.6	57.0	84.5	7.70	95.1	35.3
135	360	4.24	336	8.4	58.0	59.2	85.7	7.72	93.5'	39.8'
155	280	4.16	302	8.1	51.1	58.2	75.2	7.16	103.5'	58.3'
190	190	4.13	276	8.2	51.5	54.0	66.8	6.98	103.1'	53.8'

' Ply weaker than bond

The results obtained for the beater run on the unbleached sulfite are presented in Tables XLIV to XLVIII. Table XLIV and Figure 25 present the results obtained on the thin single sheets, Table XLV and Figure 26 those on the heavy single sheets, and Table XLVI and Figure 27 those obtained for the two-ply sheets with both plies the same. Table XLVII and Figure 28 show the results obtained for the two-ply sheets, the top plies of which were made from unbleached sulfite with a freeness of 775. Table XLVIII and Figure 29 present the results obtained for the two-ply sheets, the bottom plies of which were made from unbleached sulfite with a freeness of 380. Figure 30 shows the relationship between the perpendicular bonding values and the Mullen values for all these sheets.

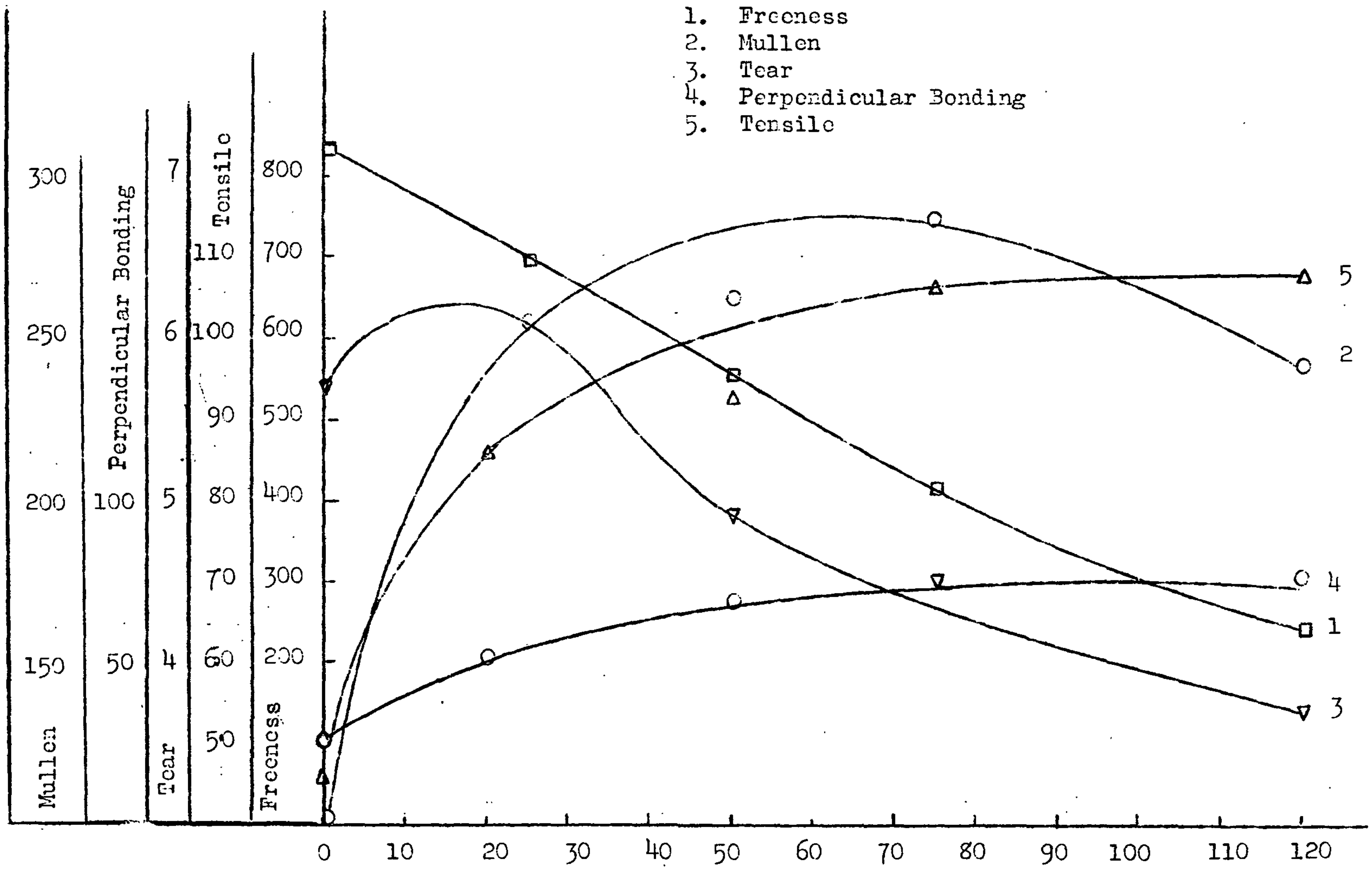


FIGURE 25. EFFECT OF BEATING ON UNBLEACHED SULFITE

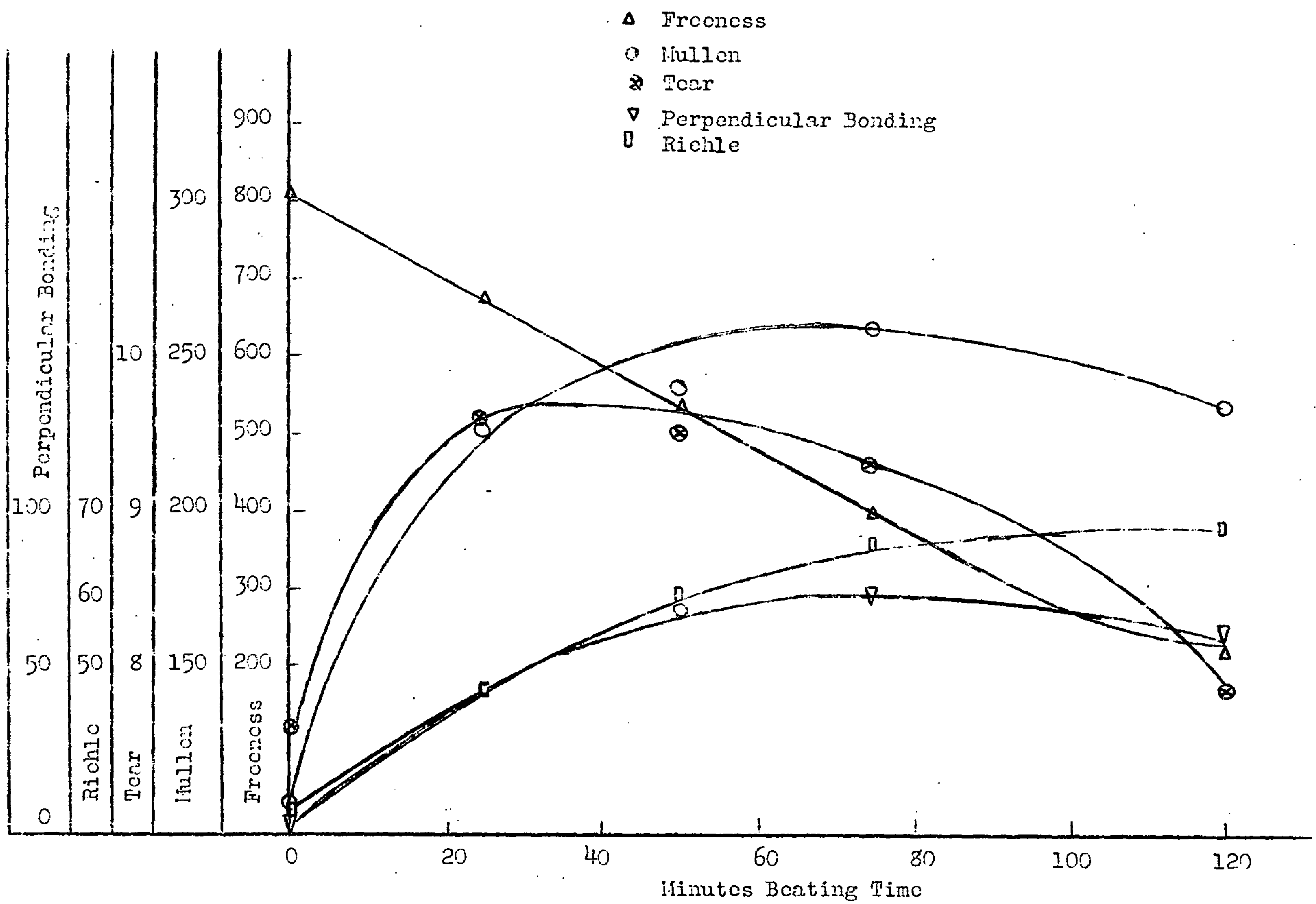


FIGURE 26. EFFECT OF BEATING ON UNBLEACHED SULFITE--THICK SINGLE SHEETS

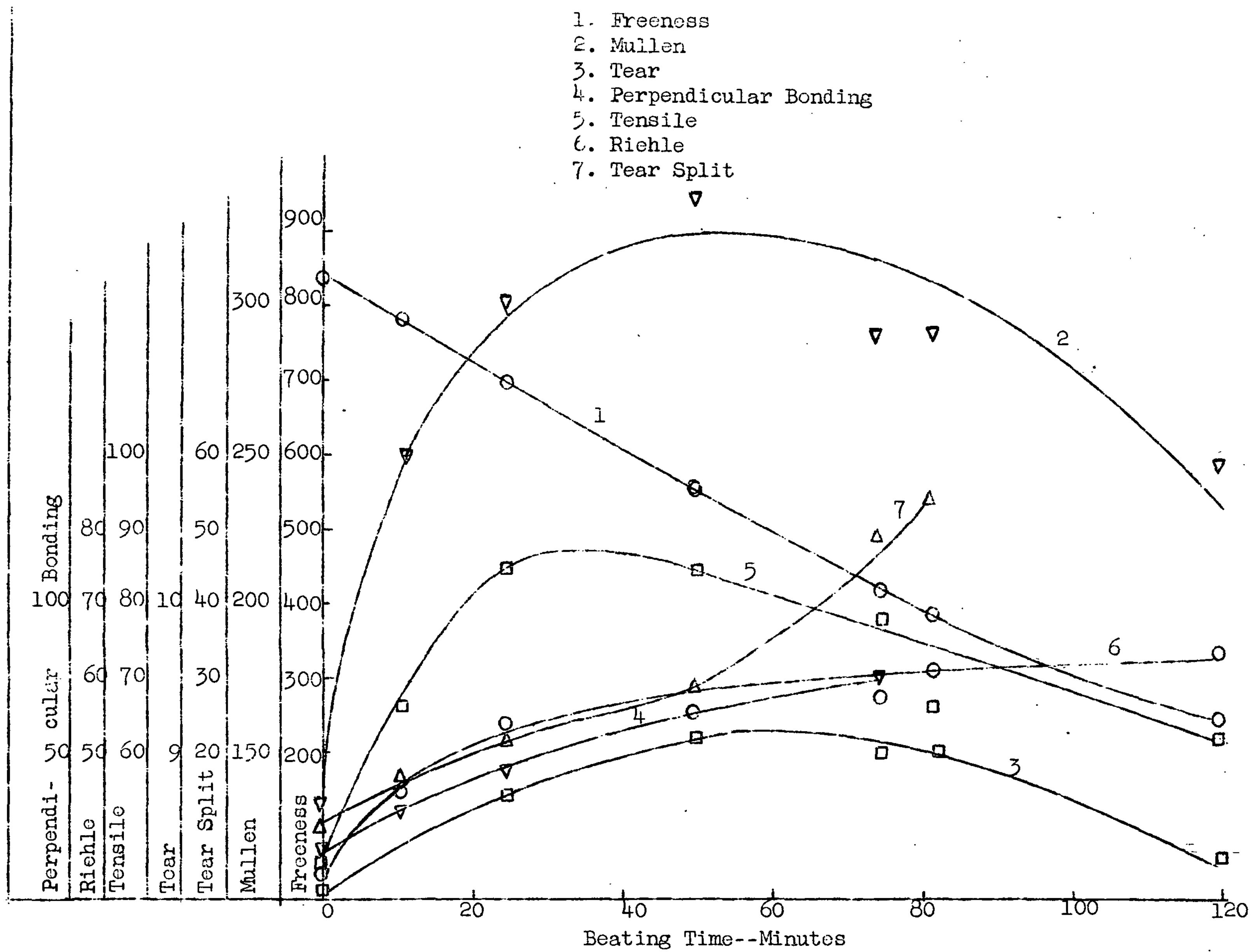


FIGURE 27. EFFECT OF BEATING ON UNBLEACHED SULFITE--TWO-PLY SHEETS

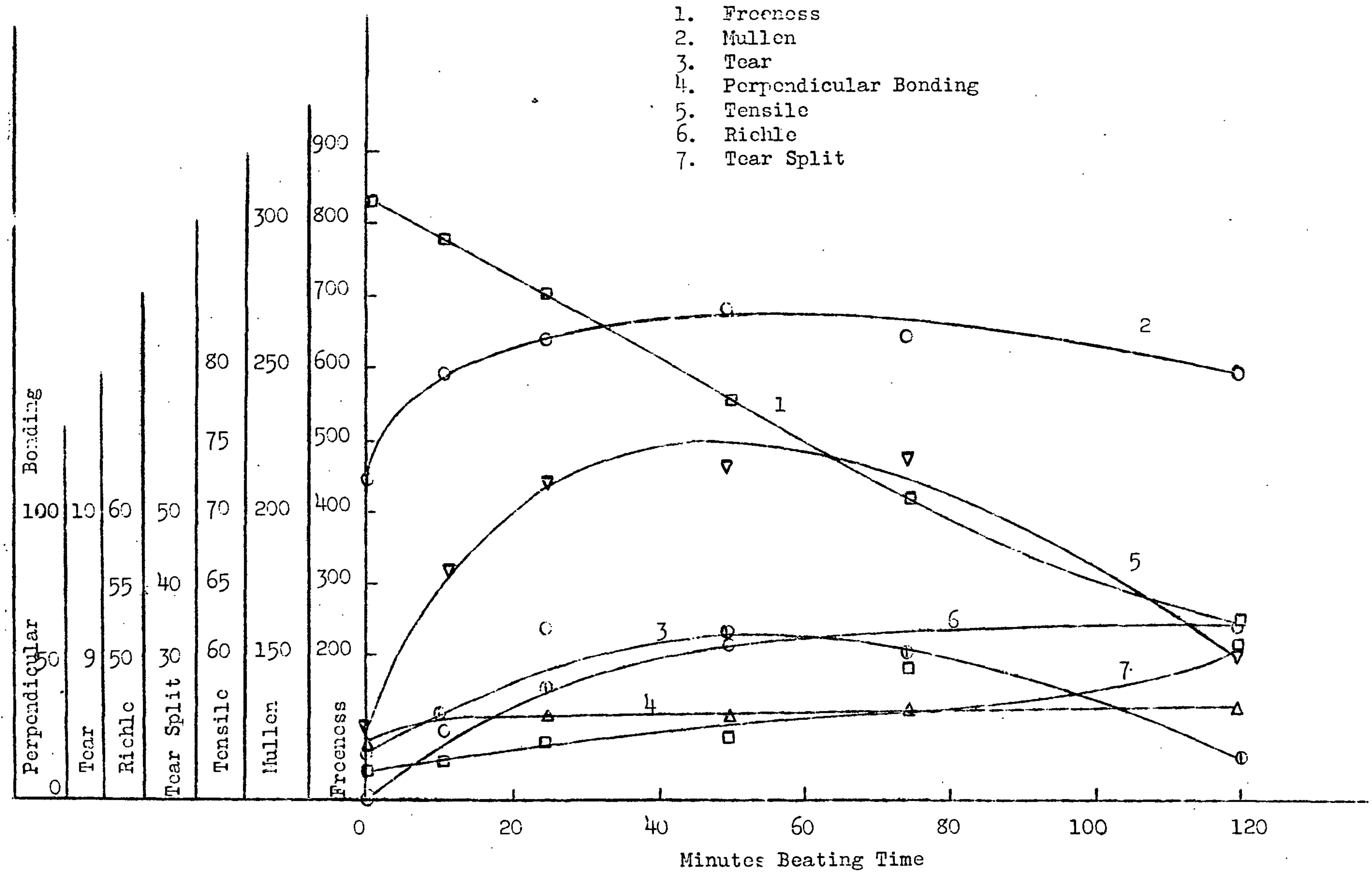


FIGURE 28. EFFECT OF BEATING ON UNBLEACHED SULFITE--ONE PLY FREENESS 775 TWO-PLY SHEET

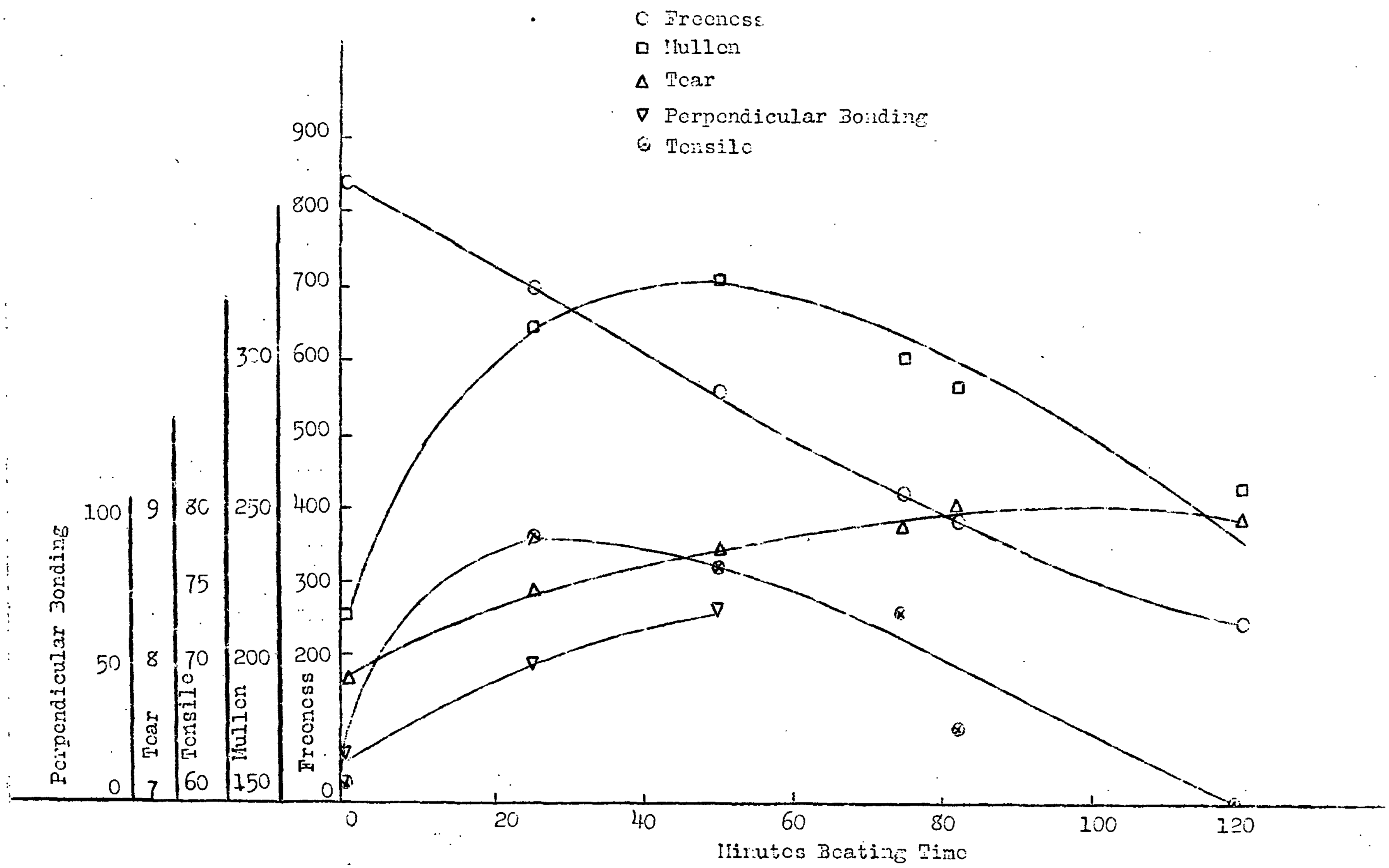


FIGURE 29. EFFECT OF BEATING ON UNBLEACHED SULFITE--TWO-PLY, ONE-PLY, FREENESS 380

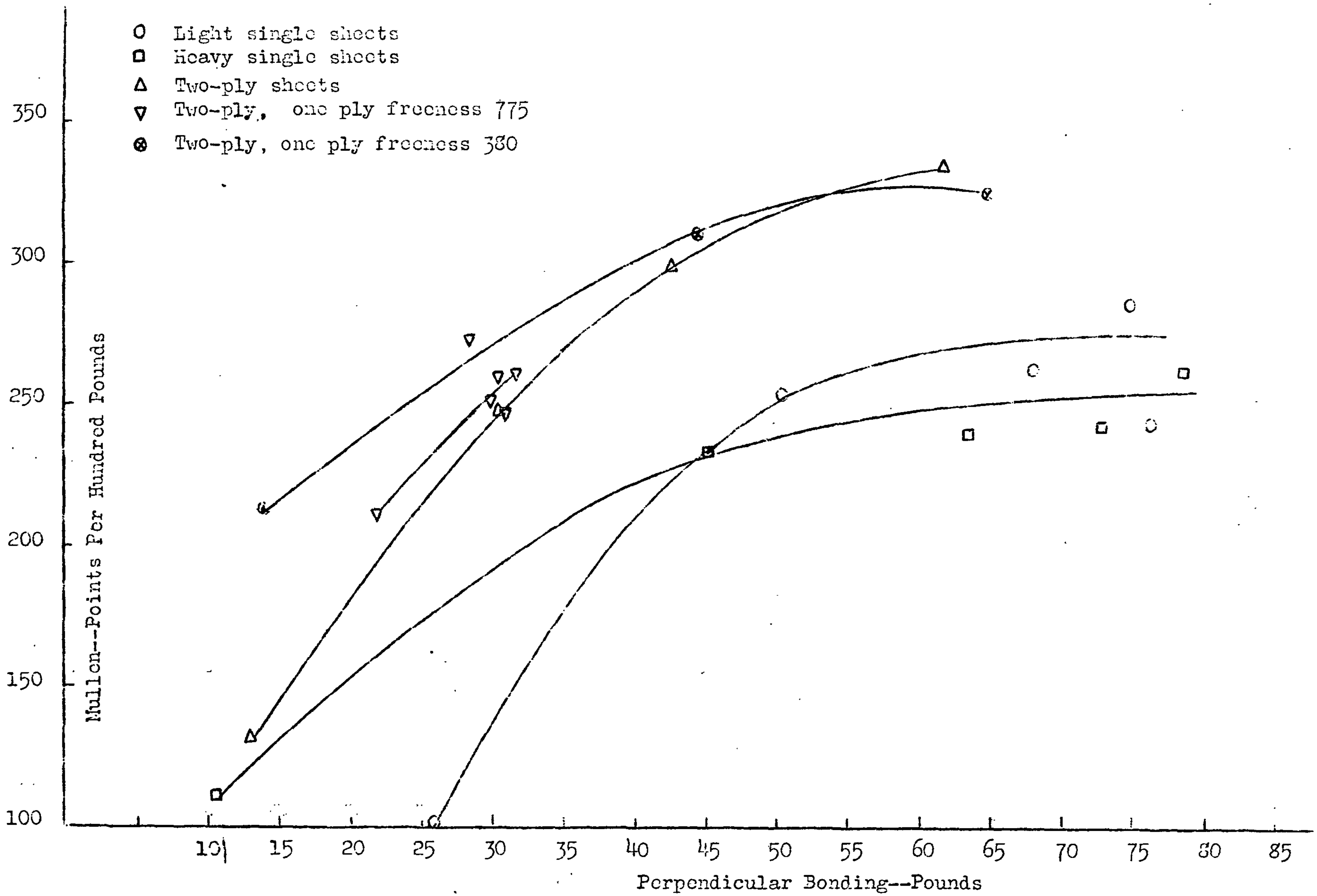


FIGURE 30. PERPENDICULAR BONDING vs MULLEN

TABLE XLIV

EFFECT OF BEATING ON UNBLEACHED SULFITE--THIN SINGLE SHEETS

Minutes	Freeness	App. Dens.	Mullen	Tear	Fold	Tensile	Stretch	Perpendicular Bonding
0	830	2.58	101	5.70	7	44.2	2.20	25.9
25	690	2.88	254	6.05	131	85.9	3.22	50.6
50	550	3.07	262	4.85	604	93.1	3.10	67.9
75	415	3.04	286	4.46	990	106.1	3.16	75.1
120	245	2.66	244	3.74	1631	107.8	3.92	76.6

TABLE XLV

EFFECT OF BEATING ON UNBLEACHED SULFITE--THICK SINGLE SHEETS

Minutes	Freeness	App. Dens.	Mullen	Tear	Riehle	Tensile	Stretch	Perpendicular Bonding
0	830	3.13	110	7.70	32.8	42.2	3.26	10.6
25	690	3.91	232	9.71	48.4	79.0	3.88	45.7
50	550	3.92	246	9.63	60.9	62.5	4.46	73.0
75	415	4.06	263	9.36	67.6	81.0	4.04	78.7
120	245	4.34	240	7.96	67.9	95.1	3.34	63.4

TABLE XLVI

EFFECT OF BEATING ON UNBLEACHED SULFITE
TWO-PLY SHEETS, BOTH PLIES THE SAME

Minutes	Freeness	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpendicular Bonding	Tear Split
0	830	3.56	131	8.0	31.0	38.8	43.6	3.56	13.0	9.9
11	775	4.04	248	8.6	45.1	46.5	65.9	5.22	30.7	15.6
25	690	4.08	299	8.7	52.5	44.3	84.2	5.68	42.6	22.1
50	550	4.18	334	9.1	54.8	43.7	83.5	5.94	61.6	28.3
75	415	4.03	290	9.0	57.1	43.5	77.7	7.34	73.9	48.8
82	380	4.22	290	9.0	61.1	40.6	65.4	7.18	66.9'	53.7
120	245	4.13	246	8.3	63.6	36.4	61.7	7.10	69.5'	----'

' Ply weaker than bond

TABLE XLVII

EFFECT OF BEATING ON UNBLEACHED SULFITE
TWO-PLY SHEETS, TOP PLY FREENESS 775

Min-utes	Free-ness	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpen-dicular Bonding	Tear Split
0	830	3.88	210	8.4	39.5	49.0	55.1	4.20	22.1'	14.6
11	775	4.04	248	8.6	45.1	46.5	65.9	5.22	30.7	15.6
25	690	3.98	258	8.8	52.0	45.5	71.7	6.50	30.7	18.6
50	550	4.09	270	9.2	51.3	49.0	72.7	5.92	28.5'	19.1
75	415	4.12	259	9.0	49.7	43.5	74.0	5.94	31.4'	29.6
120	245	4.20	250	8.3	52.3	40.4	60.0	6.04	30.3'	30.9

' Freer sheet weaker than bond

TABLE XLVIII

EFFECT OF BEATING ON UNBLEACHED SULFITE
TWO-PLY SHEETS, BOTTOM PLY FREENESS 380

Min-utes	Free-ness	App. Dens.	Mullen	Tear	Riehle	Suvant	Tensile	Stretch	Perpen-dicular Bonding	Tear Split
0	830	3.84	212	7.8	48.0	31.4	61.4	5.64	14.1	18.1
25	690	4.17	310	8.4	60.3	36.4	78.4	6.86	44.6	44.7
50	550	4.22	326	8.7	62.8	34.8	75.7	7.90	65.1'	57.1
75	415	4.27	298	8.9	59.4	39.7	72.8	6.68	73.2'	----'
82	380	4.22	290	9.0	61.1	40.6	65.4	7.18	66.9'	----'
120	245	4.14	250	8.9	61.1	30.6	59.7	6.26	72.1'	----'

' Freer sheet weaker than bond

The results obtained for the pebble mill run on the unbleached sulfite are presented in Tables XLIX to LI.

The pebble mill run was carried out by milling in the Abbé pebble mill for different times, 90 grams of pulp, disintegrated by 75,000 revolutions of the British disintegrator, with three liters of water. Seventy-seven flint pebbles weighing 5000 grams were used in the mill which rotated at the rate of 60 r.p.m. After milling, the stock was stirred for 15 minutes in 10 liters of water with a small Lightnin' mixer.

Table XLIX and Figure 31 show the results obtained for thin single sheets, Table L and Figure 32 for the thick single sheets, and Table LI and Figure 33 for the two-ply sheets. Figure 34 represents graphically the relation between the perpendicular bonding values and the Mullen values for these three types of sheets.

TABLE XLIX

EFFECT OF MILLING ON UNBLEACHED SULFITE--THIN SINGLE SHEETS

Hours	Freeness	App. Dens.	Mullen	Tear	Fold	Tensile	Stretch	Perpendicular Bonding
0.0	790	2.62	131	6.3	13	48.8	3.36	30.5
0.5	755	2.92	220	7.2	103	61.5	4.10	68.9
1.0	685	2.89	255	6.1	369	71.1	5.24	90.1
1.5	560	2.61	278	5.1	466	80.4	6.08	120.5
2.0	480	2.99	272	4.6	469	76.1	5.64	118.0
3.0	230	3.29	304	4.4	2290	80.6	7.08	169 +
4.0	155	3.45	280	4.0	1862	82.0	6.16	148.3

TABLE L

EFFECT OF MILLING ON UNBLEACHED SULFITE--THICK SINGLE SHEETS

Hours	Free-ness	App. Dens.	Mullen	Tear	Riehle	Tensile	Stretch	Perpen-dicular Bonding
0.0	790	3.54	200	7.4	23.3	54.0	5.20	37.2
0.5	755	3.82	258	9.3	45.5	59.5	5.66	85.1
1.0	685	4.00	281	9.4	53.1	69.1	9.12	109.4
1.5	560	4.55	311	9.2	50.2	77.0	9.78	129.9
2.0	480	4.25	306	8.7	63.1	75.3	10.96	133.6
3.0	230	4.99	306	9.5	92.0	72.3	16.28	174.0
4.0	155	4.91	282	8.8	89.5	56.9	13.70	185.8

TABLE LI

EFFECT OF MILLING ON UNBLEACHED SULFITE
TWO-PLY SHEETS, BOTH PLIES THE SAME

Hours	Free-ness	App. Dens.	Mullen	Tear	Riehle	Tensile	Stretch	Perpen-dicular Bonding	Tear Split
0.0	790	3.65	224	8.2	29.2	63.5	6.42	32.1	5.9
0.5	755	4.05	303	8.8	49.2	74.1	6.80	68.3	12.6
1.0	685	4.10	331	9.2	48.6	77.3	9.62	110.6	26.2
1.5	560	4.38	322	9.4	64.0	81.5	10.14	123.3	33.2
2.0	480	4.46	338	9.8	61.8	67.8	11.72	145.4	29.5
3.0	230	4.83	344	8.6	76.4	72.4	15.62	151.2'	----'
4.0	155	5.11	288	8.2	86.3	63.6	16.42	200.+'	----'

' Ply weaker than bond

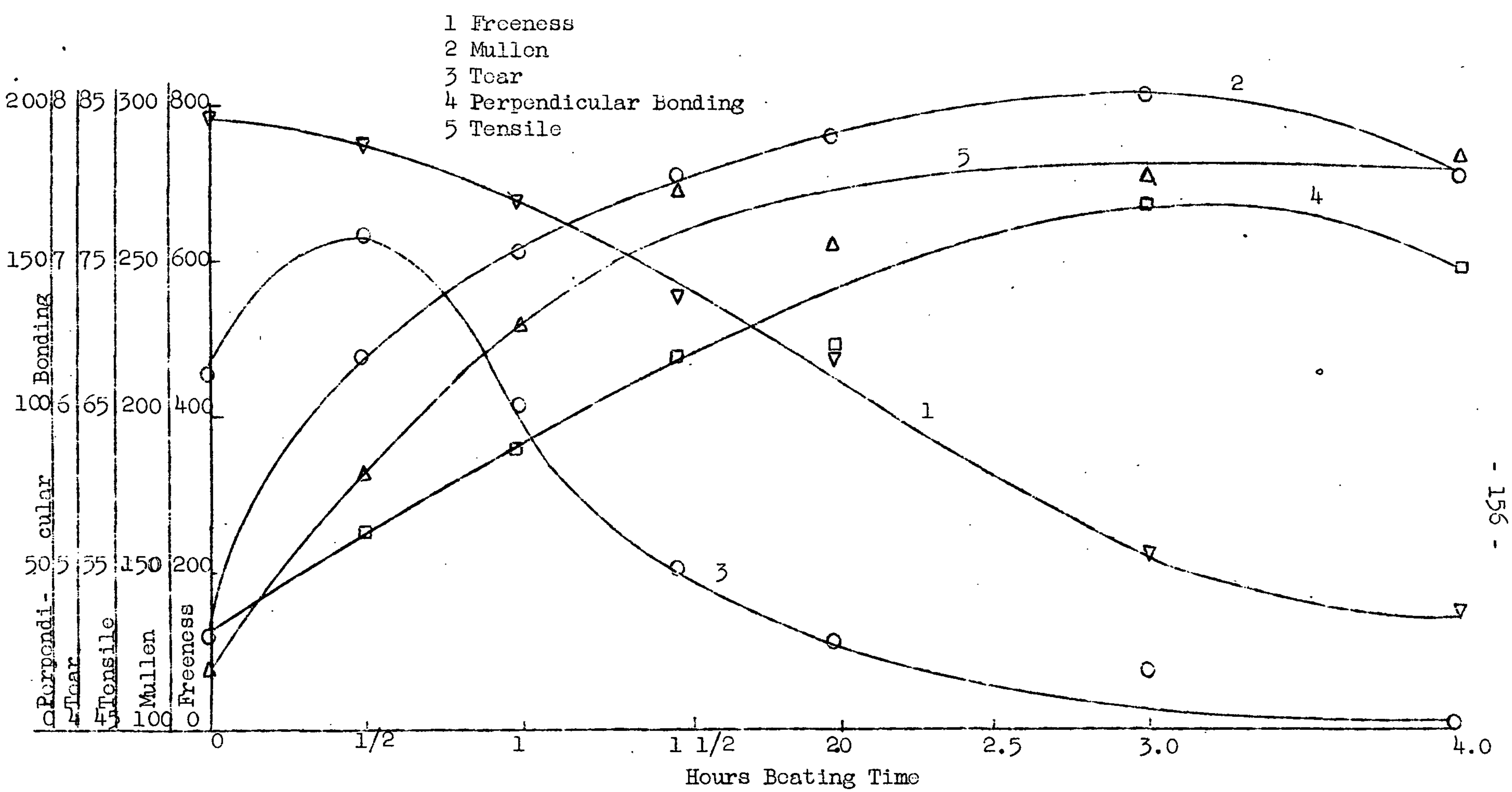


FIGURE 31. EFFECT OF MILLING ON UNBLEACHED SULFITE--THIN SINGLE SHEETS

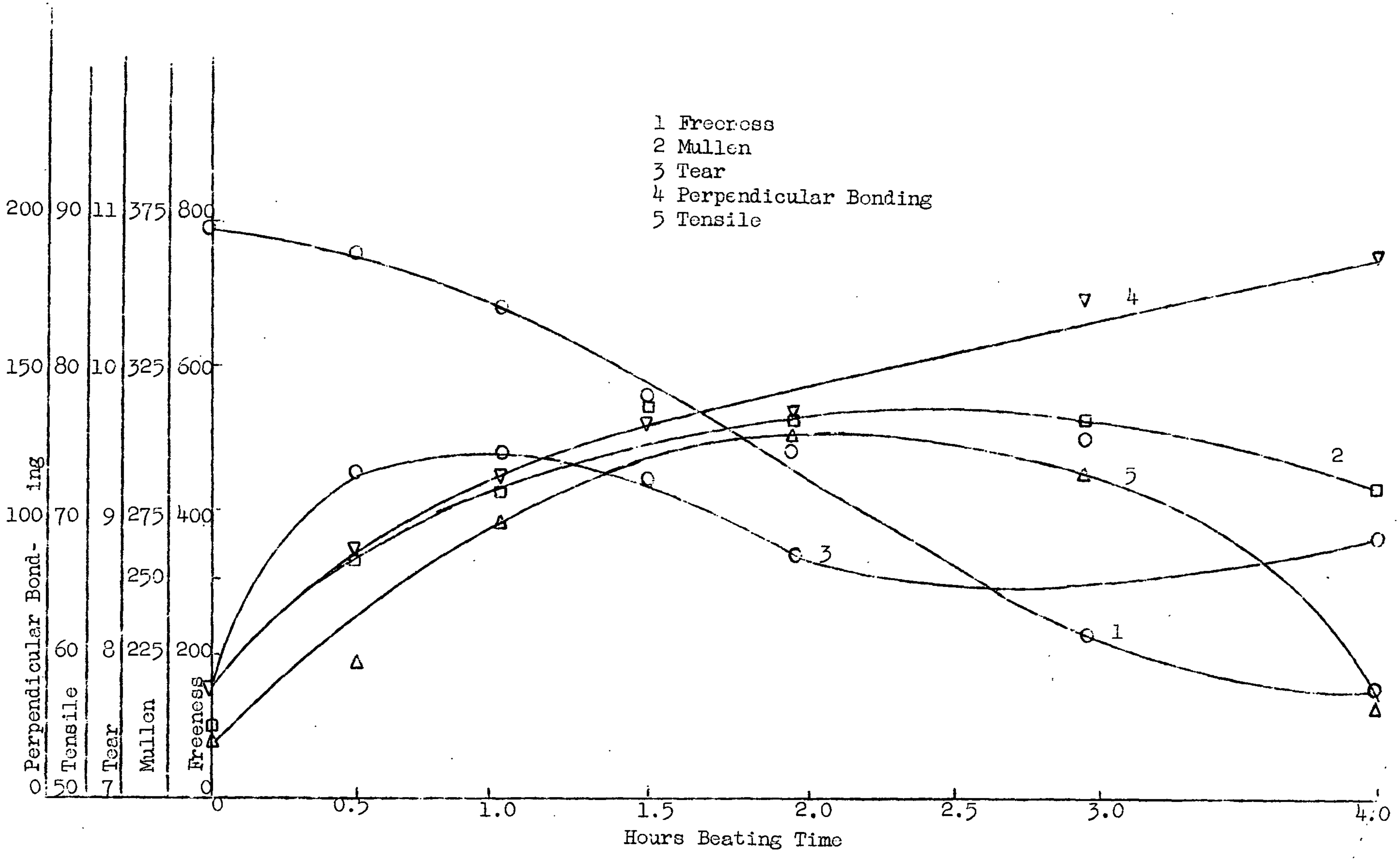


FIGURE 32. EFFECT OF MILLING ON UNBLEACHED SULFITE--THICK SINGLE SHEETS

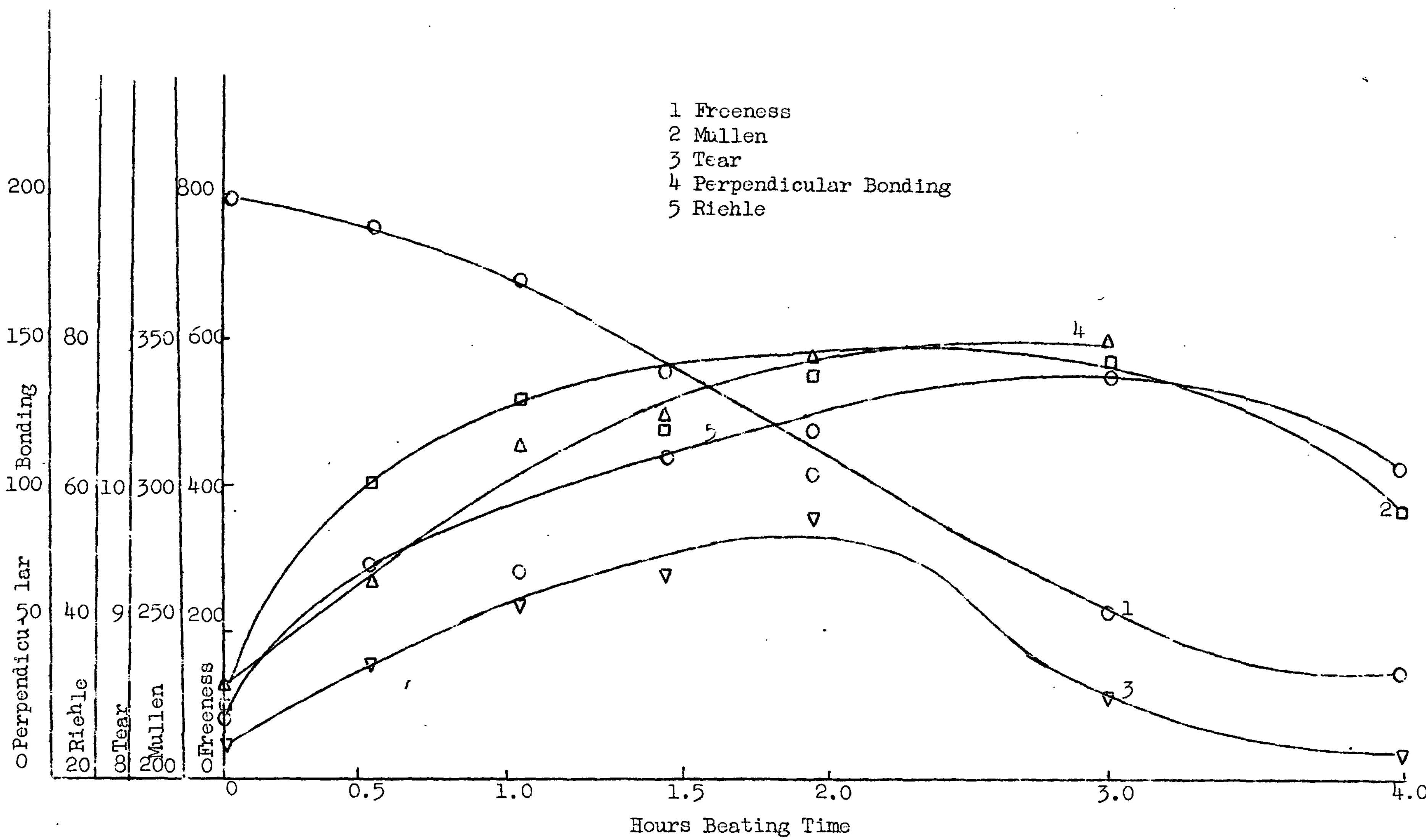


FIGURE 33. EFFECT OF MILLING ON UNBLEACHED SULFITE--TWO-PLY SHEETS

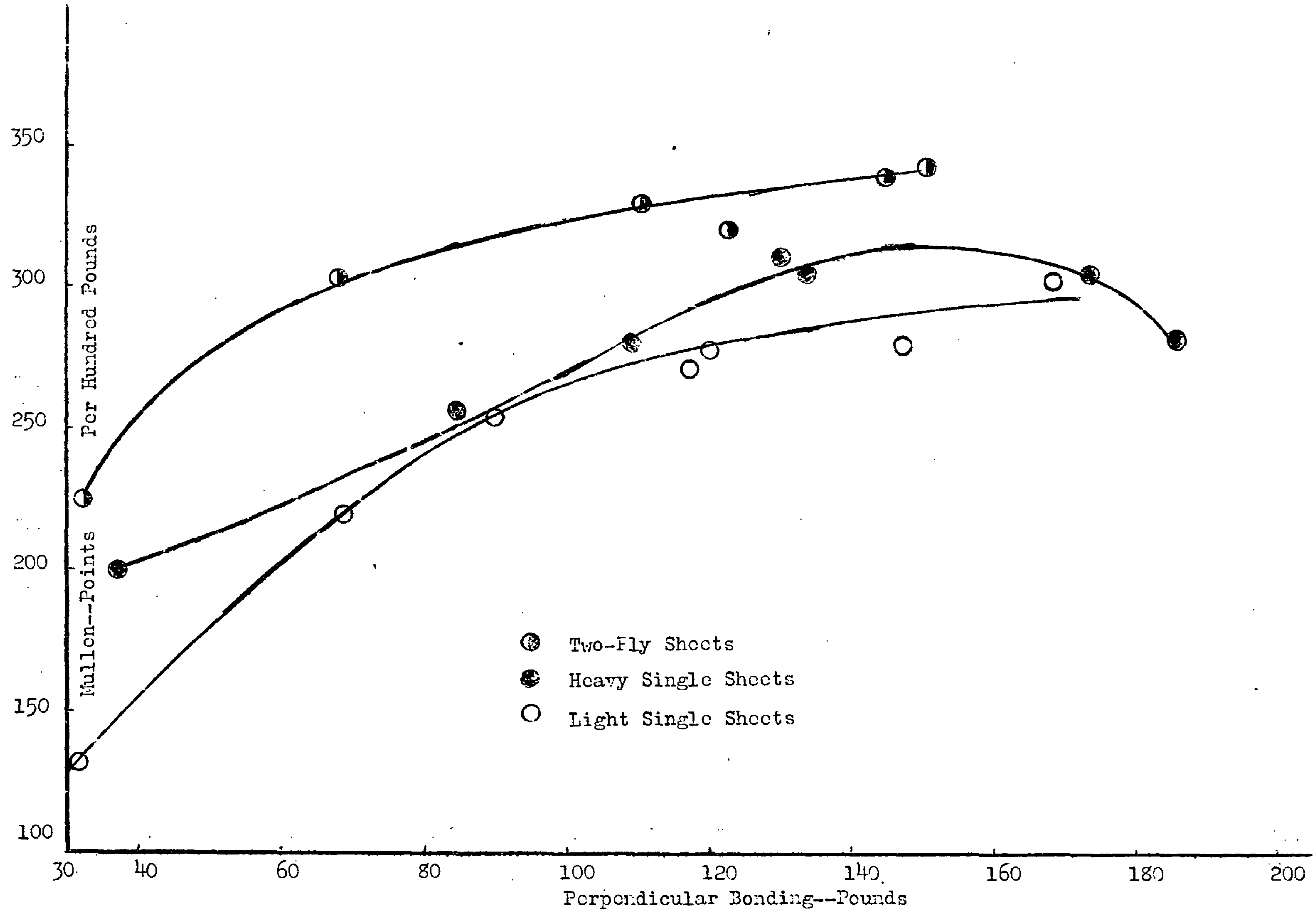


FIGURE 34. PERPENDICULAR BONDING vs MULLEN

Beating increases the bonding between plies more than any other operation in the preparation of multi-ply sheets.

On the basis of the idea that any treatment which increases the actual area of contact between plies will increase the strength of the bond between them or that, for the same amount of bonding area, the force is always the same, it may be said that beating makes a greater area of contact possible and therefore causes a higher bonding force between plies. Beating does not change the force which holds a unit area of contact together.

The manner in which beating increases the contact area between plies is very similar to that in which the bonding between fibers inside the plies increases with beating. The beating operation fibrillates the fibers, giving rise to greater surface area per fiber and a greater water-holding capacity. Likewise, it permits the production of a sheet with a smoother surface. Therefore, when two plies are joined together, the ones that are more beaten will have a smoother surface, larger fiber surface, and more water present during the pressing operation. These produce a greater area of contact and thus a stronger bond as the beating is increased.

When the beating has been carried past a certain point, an attempt to split the two plies results in the sheets splitting inside one of the plies rather than at the interface between the plies. This always happens when the stock is beaten sufficiently. The freeness at which this type of split will begin is dependent on the kind of stock and the nature of the beating action; it is at a freeness of about 400 for unbleached sulfite beaten in the laboratory beater.

The cementing structure between plies is the same as that between fibers. This must be so, because there is no material introduced at the interface between plies that is not present at the interface between fibers. Therefore, the bond between fibers should be no less than the bond between plies. Actually, the force holding the fibers together might be greater than that holding the plies together, not because of greater bonding, but because of the effect of intermeshing of the fibers during the formation of the sheet.

To explain the splitting inside the ply, it is necessary to return to the idea of the three fundamental strengths which exist in a multi-ply sheet. The bonding between plies and between fibers are equal when the plies are made from the same stock. The use of two-ply sheets reduces the effect of water removal across the ply interface during the pressing operation. Therefore, for the plies to split rather than the bond between them, the third strength, namely, that of the fiber itself, must be the weakest strength in the sheet and the one measured by the perpendicular bonding test.

The bonding between plies increases with beating until it is greater than the strength of the fiber itself. Beyond this point the bonding between plies and fibers still continues to increase, but the over-all strength of the sheet becomes less due to the decreasing fiber strength. If the fibers are allowed to retain more of their original strength (by milling rather than beating the stock), the bonding between plies will increase to a greater value before the bonding strength becomes greater than the strength of the fibers.

A consideration of the relation between the Mullen tests and the bonding between fibers and plies shows a close correlation. A comparison of the perpendicular bonding between fibers in a heavy single sheet with the Mullen strength of that sheet, reveals that the Mullen has its maximum at the point where the bonding between fibers is at a maximum. This might be expected.

The Mullen strength is dependent on the tensile strength of the sheet, and this is dependent in the weakest strength in the sheet. At the beginning of the beating, the bonding between fibers is the weakest strength in the test strip. However, as the amount of beating is increased, the bonding becomes greater and the strength of the fiber becomes less, until a point is reached beyond which the bonding strength is greater than the fiber strength. Therefore, the Mullen test is dependent on the bonding between fibers up to the point where the test shows a maximum. Beyond the maximum, the Mullen strength is dependent on the strength of the fibers. Thick heavy sheets are more applicable to considerations like this, because if two-ply sheets are used, the splitting inside the plies complicates the study, and if thin single sheets are used, the thinness of the sheets and the small change in the apparent density do not allow the bonding between fibers to be sufficiently great.

The data obtained for the effect of beating on properties other than the bonding between plies require but little explanation. It will be noted that a heavy sheet does not show a typical tear curve on beating. This is due to a partial splitting of the sheet rather than a clean tearing; however, it must be remembered that for use requirements it is usually the magnitude of the force that is important and not the kind of tear. The stiffness of the sheets increases with beating. The tensile strength of the sheets usually follows the Mullen strength quite closely.

When the results obtained on the mixed two-ply sheets are studied, it will be observed that the presence of one ply of constant composition alters the rate and magnitude of change in the strength and bonding results as the amount of beating of the other ply is changed. The use of a free ply slows up the rate of change of the Mullen for the overall sheet and reduces the value which the Mullen reaches at maximum. The use of a slow stock as the constant ply increases the rate of change and the magnitude of the Mullen, causing the maximum to be reached sooner.

It will also be observed that increasing the ability of one ply to bond will cause an increase in the bonding between that ply and a ply with constant bonding characteristics. The increase will continue until the bond between the plies is greater than the bond between the fibers plus the effect of the fiber intermeshing in the freer ply, so that the freer ply splits rather than the bond.

A consideration of the perpendicular bonding test and its relation to the Mullen strength shows that the bonding and the Mullen increase at about the same rate at first, but that at the higher degrees of beating the bonding increases more rapidly than the Mullen.

Effect of pH on the Strength and Bonding

The effect of pH on the strength and bonding for two-ply sheets, with a basis weight of about 64 pounds, made from unbleached sulfite with a freeness of 685, was studied. The bonding and the ash content of single sheets made under the same conditions as the two-ply sheets were also determined. These sheets had a basis weight of about 54 pounds. The various pH's were obtained with 5 per cent alum (on the basis of the fiber) and sodium hydroxide or sodium hydroxide alone when the pH was on the alkaline side. When the pH desired was on the acid side, it was obtained either by the use of alum or sulfuric acid.

In two cases, rosin size was used in conjunction with alum. One time the pH desired was obtained with alum alone, the other time it was obtained by using 8 per cent alum and white water. Two per cent rosin size was used in both cases.

The pH was determined colormetrically between 7.0 and 3.6. Outside this range, determinations were made electrometrically.

The sheets were all made from a suspension of stock at a consistency of about 0.2 per cent. The single sheets were pressed with a force of 66.7 pounds per inch; the two-ply sheets were couched with 3.3 and pressed with 66.7 pounds per inch force.

Table LII presents the results obtained for the two-ply sheets made using alum, and Table LIII those obtained without alum. Table LIV shows the bonding between fibers inside the single sheets, as well as the ash content of those sheets for which alum alone was used in obtaining the desired pH. Figure 35 represents some of the results in a graphic form.

TABLE LII

EFFECT OF pH ON PROPERTIES OF TWO-PLY SHEETS, ALUM USED

pH	Alum %	Free-ness	App. Dens.	Mullen	Tear	Tensile	Stretch	Riehle	Tear Split	Perpendicular Bonding
9.4	5	660	4.08	284	8.93	69.2	4.44	51.5	19.7	64.4
8.5	5	665	4.20	281	9.33	73.2	4.78	56.0	36.7	62.6
7.7	5	665	4.22	291	8.10	80.8	5.10	57.9	18.3	60.2
6.4	5	660	4.08	282	8.45	86.7	4.78	57.1	29.4	72.9
5.8	10	620	4.18	240	8.69	66.0	4.84	49.4	19.4	54.0
5.2	15	600	4.23	229	8.10	51.5	5.06	49.1	18.3	49.5
5.2	17'	610	4.19	254	8.48	56.3	5.72	52.8	9.4	48.2
4.6	20	645	4.18	249	8.48	56.1	6.10	53.8	13.9	50.9
4.2	45	650	3.96	236	7.72	76.6	5.02	49.0	24.4	60.6
4.2	8"	615	3.91	268	8.34	73.8	4.68	55.5	20.6	64.7

' 2% size added
" 2% size added, white water used

TABLE LIII

EFFECT OF pH ON PROPERTIES OF TWO-PLY SHEETS, NO ALUM USED

pH	Free-ness	App. Dens.	Mullen	Tear	Tensile	Stretch	Riehle	Tear Split	Perpendicular Bonding
9.4	705	4.08	286	9.20	73.0	4.74	55.2	28.9	65.0
8.5	670	4.09	282	8.39	75.6	4.84	59.0	26.5	67.9
7.7	680	4.18	288	9.02	85.5	4.80	57.1	23.4	59.2
7.0'	685	4.08	291	8.25	84.5	5.12	54.9	22.6	66.2
6.4	680	4.13	279	8.69	83.6	5.48	55.2	33.7	63.4
5.8	695	4.12	291	7.45	78.0	5.18	53.6	27.5	66.2
5.2	690	4.24	302	8.41	89.7	4.92	52.1	21.3	65.8
4.6	670	4.19	308	9.23	66.4	5.12	59.1	26.6	64.5
4.2	670	4.00	293	9.04	64.8	5.28	56.1	30.2	64.9
3.6	690	4.07	301	9.66	79.1	5.26	49.8	29.0	62.2
3.0	690	4.11	286	8.95	78.8	5.26	52.2	31.4	61.7
2.3	705	4.03	194	5.60	55.8	2.70	50.3	19.0	62.3

' Nothing added

TABLE LIV

EFFECT OF pH ON BONDING BETWEEN FIBERS

pH	Alum %	Perpendicular Bonding	Ash %
9.4	5	68.5	----
8.5	5	64.4	----
7.7	5	65.3	----
6.4	5	71.6	0.89
5.8	10	56.1	1.97
5.2	15	37.9	2.55
5.2	17'	33.0	----
4.6	20	47.8	2.14
4.2	45	55.3	1.53
4.2	8"	76.3	----
9.4	--	70.5	----
8.5	--	68.7	----
7.7	--	66.6	----
7.0	--	64.0	0.35
6.4	--	66.3	----
5.8	--	70.9	----
5.2	--	65.8	----
4.6	--	63.1	----
4.2	--	54.7	----
3.6	--	59.0	----
3.0	--	60.4	----
2.3	--	55.3	----

' 2% size added

" 2% size added, white water used

Changing the pH of the suspension from which the sheet is formed changes the strength properties and the bonding in the sheet. The bonding between fibers in a single sheet closely parallels the bonding between plies in a two-ply sheet made from the same stock.

Decreasing the pH in the presence of 5 per cent alum from 9.4 to 7.6 causes a reduction in the bonding between plies, whereas between 7.6 and 6.4 there is a rapid increase

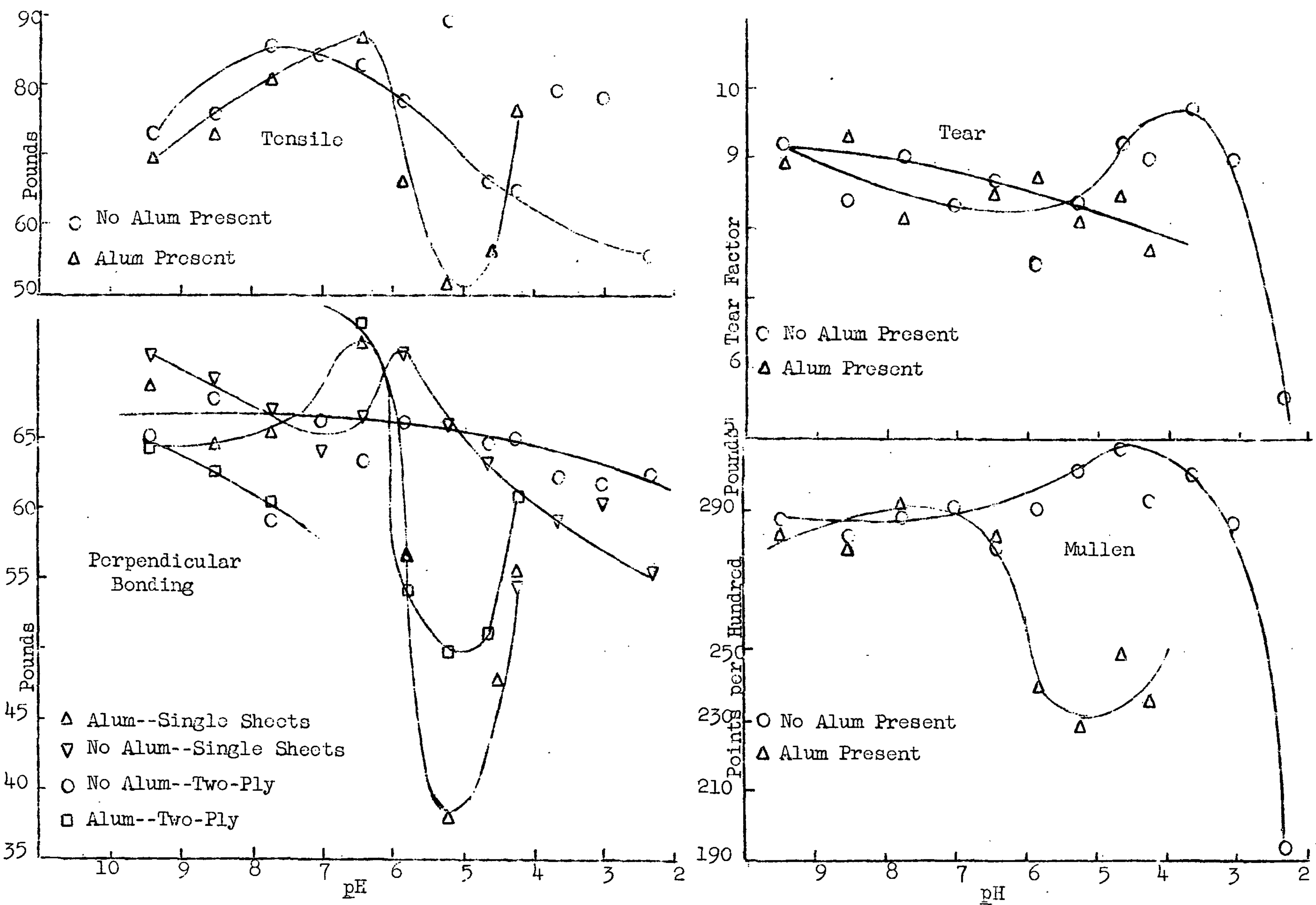


FIGURE 35. EFFECT OF pH

in the bonding. As the amount of alum added to decrease the pH is increased, the bonding between plies passes through a minimum at a pH of 5.2, corresponding to an addition of 15 per cent alum. Increasing the quantity of alum added beyond this point causes the bonding to increase rapidly.

Single sheets behave almost in the same way in the presence of alum, giving the maximum and minimum at the same pH's as indicated for the two-ply sheets. The only difference is that the bonding on the alkaline side may be said to increase as the pH is reduced, but this effect is not definite and may not exist.

When no alum is present, the bonding between two plies shows a very slight decrease as the pH is changed from 9.5 to 2.3. On the other hand, the bonding in single sheets changes as the pH is changed. Upon decreasing the pH from 9.5 to 7.0, the bonding decreases. Between 7.0 and 5.8 it increases, passing through a maximum at a pH of 5.8. At pH's below this, the bonding decreases regularly from the maximum.

The explanation of the minimum in the results obtained at 5.2 is based essentially on the amount of alumina retained in the sheet as a filler; the ash content of the single sheets bears this out. There is a maximum in the ash content at the point where there is the minimum in the bonding, tensile, and bursting strengths. The differences in the ash content are a result of the solubility of alumina floc in alum solutions. It was observed that as alum was added to tap water, a floc was formed at first, but as the alum addition was continued the amount of floc increased up to a certain point, beyond which, the floc began to go back into solution and, when sufficient alum had been added, no precipitate was visible in the solution. Added to the effect of the filler, there is probably the effect of the changing electrostatic charge on the fibers as the pH is changed by the addition of alum.

On the alkaline side, decreasing the pH with a constant amount of alum present caused a decrease in bonding. Work carried out by Collins (31) on the cataphoretic nature of the alumina floc in water showed that the zeta-potential of the floc decreased as the pH is reduced from about 9.5 to 7.5. It is therefore believed that the decreasing zeta-potential influences the way the sheets form and the fibers bond together.

Collins also found that he was unable to determine the zeta-potential of the alumina floc by cataphoretic methods between the pH's of about 7.5 and 6.3. However, below this range the charge on the fiber had been reversed and was negative instead of positive as it was above this range. The more the pH was reduced, the more negative the charge became down as far as a pH of about 4.0, beyond which the floc dissolved. A pH of about 7.0 is therefore believed to be the isoelectric point of the alumina floc prepared by dissolving alum in water.

Since there is the rapid change in the nature of the alum floc at a pH of about 7.0, it is reasonable to believe that the bonding in a sheet made in the presence of alum may change rapidly at this pH. On this basis, the rapid increase in the bonding in going from the alkaline to the acid medium may be explained.

A complete study of the effect of pH and alum on the strength and bonding in sheets should be undertaken. Special emphasis should be given to the bonding test as a measure of one of the fundamental strengths of the sheet. However, time was not available to undertake such a study in the present investigation.

Apparently pH alone does not affect the bonding between plies, but it does affect the bonding between fibers. This conclusion is based on the results obtained when sodium hydroxide or sulfuric acid alone were used to obtain the desired pH. The changes are probably caused by a change in the zeta-potential possessed by the fibers as the pH is changed. It may also result from poorer formation which causes poorer bonding.

The Mullen strength of two-ply sheets using alum in their preparation is nearly constant as the pH is decreased from 9.5 to 6.4, with a constant amount of alum present.

When the amount of alumina retained in the sheet increases, the Mullen strength decreases, in much the same way it does when filler is added to a sheet. The decrease is probably greater than that caused by the filler action alone and may be in part due to the electrical nature of the fiber surfaces during sheet formation. This latter effect should be considered in any future study.

The tensile strength goes through a maximum and a minimum at the same pH's as the Mullen and bonding. This is also caused by the combination of the effect of alumina retained and the fiber charge. The increasing tensile strength on the alkaline side is not in accord with the constant Mullen and increasing stretch in this range.

Sheets made with alum present show a slightly decreasing tear as the pH is decreased. There is no maximum or minimum and the change is small. On the other hand, there is a maximum in the tearing strength when no alum is present. The rapid decrease at the lower pH's can be attributed to deterioration of the fibers, brought about by the large amount of acid present in the sheet at the time of drying. The cause of the maximum is not understood.

This study of pH was essentially preliminary in nature, and not enough work was done to be able to explain all the changes that take place. It is hoped that it will be useful in guiding work that may be undertaken in a future investigation on the effect of alum on the strength of sheets.

The presence of rosin size apparently does not affect the strength or bonding between plies or fibers; these are primarily dependent on the amount of alum present. Further work should be undertaken to elaborate on the effect of rosin size in this connection.

SUMMARY AND CONCLUSIONS

The plies in a multi-ply sheet are bonded together in the same way as the fibers are bonded inside the plies. All conditions being equal, the bonding between plies has the same magnitude, if not the same value, as the bonding between fibers inside the plies.

The strength of the bond between fibers and plies can be increased by increasing the area of actual contact between them. The nature of the cementing structure is not changed when the bonding strength changes; it is merely the amount that is changed.

The amount of water in the sheet at the time of final pressing is important in determining the area of contact between plies in a multi-ply sheet. The greater the amount of water present during pressing, the greater the strength of the bond between fibers and plies; however, if this water content is too high, the sheet will crush during pressing, thus reducing the bonding.

There is a definite relation between the bonding between plies and the strength of a multi-ply sheet. However, any treatment which increases the bonding between plies is likely to increase the bonding between fibers. The two effects are practically inseparable and must be considered together in a study of the bonding in a multi-ply sheet. All other conditions being the same, increasing the bonding between plies will increase the strength of the sheet. The tearing strength, however, is affected in only a few cases when the sheet preparation is changed so as to alter the bonding between plies.

It is possible for the strength of the bond between plies to be greater than the weakest strength inside the plies. In as much as the bonding between plies and between fibers are nearly the same, under this condition the weakest primary strength inside the ply is the strength of the fiber itself and not the strength of the bond between fibers. This condition exists when the stock is well beaten or when two stocks, one of which is relatively unbeaten and the other well beaten, are joined together. By using a two-ply sheet instead of a single sheet and observing where the sheet splits, it is possible to determine when the fiber strength becomes less than the fiber bonding. This is not possible with a single sheet. Therefore, a two-ply sheet, rather than the single sheet itself, should be used to measure the relation between the two primary strengths in a single sheet.

Multi-ply board made with the Noble and Wood sheetmaking equipment can be duplicated approximately. Sheets made on this apparatus closely resemble those made on a cylinder machine in most of the major properties, except grain, although a small amount of grain is present in the handsheets.

The bonding between fibers and between plies is important in determining the strength of the sheet. Two types of bonding can be measured, namely, the force required to split the sheets apart by tearing and that required to pull the sheets apart when the force is applied normally to the surface of the sheet. The various tests used to measure these forces have been studied. In cases where the strength of the weakest point in a multi-ply or single sheet is to be determined, the perpendicular bonding test is applicable. When it is desired to measure the strength of the bonding between any two given plies in a multi-ply sheet, the tearing-type splitting test is recommended. A simple test of the latter type can be carried out by using the Elmendorf tear tester.

The strength of a multi-ply sheet is greater than the combined strength of the individual plies in the sheet, when the single ply is tested as a unit. Likewise, the multi-ply sheet is stronger than the individual plies when a number of plies equal to the number in the multi-ply sheet are tested as a unit. (The tensile strength is the only strength that is an exception to these conditions.) Therefore, the strength of a multi-ply sheet is dependent on the presence of the bonding between plies.

The number of plies that are used to make multi-ply sheets of the same weight affects the strength of the sheets. There is an optimum number of plies to obtain a maximum bursting strength. This number is dependent on the over-all weight of the sheets and the nature of the stock. The quality of formation and the strength of the bonding between plies are the two factors recognized as causing the type of results obtained.

In a single sheet, the bonding between fibers is not a function of the sheet weight or thickness; the fibers in the center of the sheet are bonded together with a force that is equal to that for the fibers on the surface of the sheet.

The bonding between two plies is dependent on the position of the interface in relation to the remainder of the sheet and on the nature of the remainder of the sheet. For any given position, the bonding between plies is greater if the freer stock is on the outside of the interface.

Curling of multi-ply sheets is caused primarily by the differences in the amount of shrinkage of the different stocks. A freeness test taken on the stock is not sufficient to indicate the shrinkage of the sheet. News stock shrinks but little and yet it may have a very low freeness. The sheet curls toward the most hydrated ply.

The amount of couching pressure used has little effect on the strength properties of the multi-ply sheet with the exception of the bursting strength which increases as the couching pressure is increased. For hydrated stocks, increasing the couching pressure causes the bonding between plies to decrease a little. For unhydrated stocks, the bonding between plies increases as the couching pressure is increased. The results are due to a combination of a decreasing water content at the time of pressing, resulting in decreased bonding, the ease of water removal across the interface in the pressing and drying operations, and an increasing area of contact caused by the increasing pressure.

Increasing the final pressure given a multi-ply sheet produces an effect similar to that caused by a small amount of beating. For all stocks and at all freenesses, increasing the final pressure increases the bonding between plies. The rate of increase is small above a pressing force of 50 pounds per inch on the press roll.

Calendering a sheet, whether it be a single sheet or a multi-ply sheet, reduces the strength and the bonding of the sheet. The reduction in all strength tests on two-ply sheets, except stiffness, is small if the sheet is well bonded originally. If the bonding force between plies is low before calendering, the strength and bonding will be decreased appreciably by the calendering operation.

Both the amount of drying given a two-ply sheet and the amount of moisture present in the sheet at the time of testing play major roles in determining the strength properties and the bonding between plies. The effect of moisture is greater than the effect of drying. Loss in strength on drying is related to the loss in stretch of the fibers and not to the loss in strength of the bond between plies or fibers.

The amount of beating is the most important factor in determining the amount of bonding between fibers and plies. As the beating increases, the bonding between plies increases. When the beating has been carried past a certain point, the strength of the sheet decreases, whereas the bonding continues to increase, because the strength of the fiber becomes the weakest primary strength in the sheet and is, therefore, the controlling strength in most of the tests. Beating the stock in a manner so that more of the original fiber strength is retained results in a greater over-all strength for the sheet before the fibers become the weakest point in the sheet. These considerations hold for the fibers in a two-ply sheet as well as for those in a single sheet.

When two plies made from different stocks are bonded together, the more hydrated ply is the one that governs the strength of the bond between the plies, unless the difference in beating is so great that the bonding between plies is greater than the bonding between the fibers in the freer ply. Normally, each ply tends to exert its own effect in governing the over-all strength of the sheet.

The strength of the two-ply sheet and the bonding between plies and fibers are changed by changing the pH at which the sheets are formed, both in the presence and absence of alum. The direction of the changes varies and the changes are greater if alum is present. This phase of the work should be extended by a thorough investigation.

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